

Final report

1. Project details

Project title	Energi Effektivt Access Netværk
File no.	64021-1120
Name of the funding scheme	EUDP og GLDK
Project managing company / institution	Bifrost Communications ApS
CVR number (central business register)	38748211
Project partners	DTU
Submission date	1/7/2021

2. Summary

Project summary

The purpose of the project:

The aim of this project was to develop a breakthrough fiber-optic Receiver, which increases signal detection by more than 10 times.

This would allow for a substantial reduction in the number of central offices needed for internet data distribution and thereby a reduction in power consumption and CO2 emissions caused by the even growing internet.

Results, conclusions and perspective

During the project was developed a ROSA based on Bulk optic in which individual optical components are aligned internally. These Bulk ROSAs were produced successfully. Moreover, Bifrost has developed a version of a ROSA, which is based on photonic integrated circuits (PIC). The PIC ROSA has the advantage that all optical functions except for the in coupling of light are integrated and aligned (almost) perfectly.

Furthermore, Bifrost has developed a fully integrated transceiver in the form-factor SFP, which is the desired form-factor used by all Operators in Access networks.

The PIC ROSA and the SFP build on the experience of the Bulk ROSA of this project and is a significant advancement for Bifrost. In fact, this is a major step up in the value chain, as we now can offer the transceiver directly to customers rather than having to convince other transceiver vendors to use our ROSA as part of their solution.

On a global scale, our technology could reduce the energy consumption of the Access Network by 50%, translating into a 30% energy reduction in the Internet industry. Bifrost Communications, a Danish start-up and spinoff from the Department of Photonics Engineering at DTU (Technical University of Denmark), has developed a groundbreaking technology called QC-ROSA (Quasi-Coherent Receiver Optical Sub-Assembly). This technology significantly enhances transceiver sensitivity in the Access Network, setting Bifrost apart in the market.

Projekteresumé

Formålet med projektet

Formålet med dette projekt var at udvikle en banebrydende fiberoptisk modtager, som øger signaldetektionen med mere end 10 gange.

Dette ville muliggøre en væsentlig reduktion af antallet af centraler til distribution af internetdata, og dermed en reduktion i strømforbrug og CO₂-udledning forårsaget af det stadigt voksende internet.

Resultater, konklusioner og perspektiv

I projektet blev der udviklet en ROSA baseret på bulkoptik, hvor individuelle optiske komponenter er justeret internt. Disse bulkoptiske ROSA'er blev produceret med succes. Derudover har Bifrost udviklet en version af en ROSA, som er baseret på fotoniske integrerede kredsløb (PIC). PIC ROSA'en har den fordel, at alle optiske funktioner undtagen lyskobling er integreret og justeret (næsten) perfekt.

Derudover har Bifrost udviklet en fuldt integreret transceiver i formfaktoren SFP, som er den ønskede formfaktor, der anvendes af alle operatører i Access netværk.

PIC ROSA og SFP bygger på erfaringerne fra Bulk ROSA fra dette projekt og er et betydeligt fremskridt for Bifrost. Faktisk er dette et stort skridt op i værdikæden, da vi nu kan tilbyde transceiveren direkte til kunden i stedet for at skulle overbevise andre transceiverleverandører om at bruge vores ROSA som en del af deres løsning.

På globalt plan kan vores teknologi reducere energiforbruget i accessnetværket med 50%, hvilket svarer til en energireduktion på 30% i internetbranchen. Bifrost Communications, en dansk startup og spin-off fra Institut for Fotonikteknik på DTU (Danmarks Tekniske Universitet), har udviklet en banebrydende teknologi kaldet QC-ROSA (Quasi-Coherent Receiver Optical Sub-Assembly). Denne teknologi forbedrer transceiverfølsomheden i Accessnetværket betydeligt, hvilket adskiller Bifrost fra andre på markedet.

3. Project objectives

An overview of the objectives of the project and a short summary of the results can be found in the following Figure 1. Due to significant delays on the Bulk ROSA housing, we started an effort on PIC ROSA, which by the end of the project caught up to the Bulk ROSA. We have chosen to include the result of the PIC ROSA in this report for comparison and because the PIC ROSA development in large part is based on the experience gained from the Bulk ROSA development. Furthermore, we have chosen to include the result of our transceiver effort as well, since this has served as the ultimate demonstration vehicle for our technology, and we are about to launch the SFP as a product. At the core of all this is the ASIC development which is where the "magic" of out QC-technology is implemented. We have chosen to include a full status overview of where we are today

even if some of this (50G and 100G) is beyond the initial scope of the project. We view the Bulk ROSA project as the originating project that shaped the foundation to our further development of the PIC ROSA and Transceiver.

	ID	Objective	Result	Comment
ASIC	10/25G	Optimize ASIC for 25Gbps (and 10Gbps) to provide DSP free dispersion compensation with up to 40km reach	25Gbps over 40km was demonstrated in combination with PIC-based ROSA. ASIC development is completed for 25Gbps 40km product both ROSA and Transceiver. New ideas are being investigated to reach 60 km and perhaps even 80 km (patent filed)	Bifrost is the only company that can reach 40km at 25Gbps DWDM. This achievement has opened up markets for upgrades in DWDM Networks both for Telecom and Cable operators
	50G	Optimize ASIC for 50 Gbps to provide DSP free dispersion compensation with up to 15km reach	First tests showed less than expected performance. Degradation is due to carrier leakage which will be reduced in follow-on ASIC designs. Last iteration showed PAM-4 eye diagram for the first time - thus we believe we are on the right track to be able to resolve the issue	Our target is to be able to provide a 50Gbps over 20km solution. This is a very unique specification of the MOPA group, and we would be the only company able to meet the requirement
	100G	Start initial work toward 100G solutions	First design for 100G ASIC is completed - awaiting results	Our 100Gbps effort is currently being pursued in collaboration with III-V Labs and Nokia. Our part is on the ASIC. We expect to start our own effort on PIC, ROSA, and Transceiver once the photo-detectors from our PIC vendors have sufficient bandwidth
Bulk ROSA	10/25G	Develop ROSA based on Bulk optic to be compatible with SFP packaging	25 Bulk-optic ROSAs were produced by You-opto and tested. 25Gbps over 30 km was demonstrated as receiver sensitivities in the range from -13 to to -15 dBm. Polarization dependency was high - up to 4 dB. In addition, 15 Bulk-optics ROSAs were produced by AVO Photonics using a revised optical design. While these ROSAs perform slightly better than the Youopto ROSAs, sample to sample variation remains high. The Bulk ROSAs were tested for all three use cases showing acceptable performance in the best cases.	The Bulk-optic ROSA has served as a great first demonstration that our technology can be packaged into a standard package for the SFP transceiver market. However, the assembly of the Bulk-ROSA is cumbersome and results in larger than desired sample-to-sample variation and polarization dependency.

PIC ROSA	25G	Develop ROSA based on PIC technology to be compatible with SFP packaging. Demonstrate combined TROSA capability	2 PIC-based ROSAs were initially produced as well as multiple TROSA PIC/ASIC combinations on test boards and in our QSPF demo. Five ROSA Units were produced for the SFP prototypes. 25Gbps over 40 km was demonstrated in both ROSA, PIC/ASIC test boards, QSFP and latest in the first SFP prototype units. Performance ranges from -17 to -19 dBm at 40Km and polarization dependency is around 1 dB.	The PIC-based ROSA demonstrates much more consistent performance and low polarization dependency. The plan is to base our first product - both Transceiver and ROSA - on the PIC-based ROSA. After initial prototyping, we plan to produce 50 units in early 2026 to qualify both ROSA and SFP as products
Transceivers	QSFP	5 QSFP units were designed and produced in collaboration with Estel and showcased at OFC 2025. These units were designed to have both tuneable lasers (from our partner Pilot in Ireland) and our own transmitter build on the same PIC as our Receiver	Several of the units had faults due to issues with the lasers or broken fibers. However, we did demonstrate the tunability as well as 25Gbps over 40 km	The QSPF demo at OFC 2025 was a great success and generated much attention and follow up customer engagement
	SFP	Design of our first transceiver product is being done in collaboration with Estel	Design is completed, material for first prototypes has been procured. First units are fully functional, and we have prototype SFP transceivers running real traffic over 40 km	Multiple units SFP prototypes were ready for demonstration at ECOC 2025 (October), and plan is to have first pilot production in early 2026. Multiple customers have expressed high interest

Figure 1 Overview of the Objectives and Results of the technical part of the project with the addition of PIC ROSA and Transceivers.

4. Project implementation

Initially, the project evolved nicely and according to plan. The first ROSAs from Youopto were designed, produce and tested (see later in report). Based on the results, a redesign and a new Contract Manufacturer, AVO, was added. However, midway in the project, AVO ran into substantial issues on the housing received from the first housing vendor, Streamtek, who could not deliver as promised. After some time, we decided to augment the housing effort by ordering housing from two additional vendors, Kyocera and First Opto. Leadtime on these new housings lead to a substantial delay of the project. However, in the meantime, we initiated an

effort to develop a PIC-based ROSA, which eventually caught up to the Bulk ROSA, in great part due to the experience we gained on the Bulk ROSA. We also developed a full transceiver in the SFP form factor, which is used in the Access Networks. Overall, we are now in a position to offer a transceiver running at 25Gbps over 40km. This transceiver has several advantages over the nearest competitor; longest reach available, lowest power consumption at this distance, and no added latency, which is an important factor in mobile fronthaul. We have great traction on this offering from several Tier 1 customers.

Risk identification and management have been handled on an ongoing basis throughout the project. Initially several risks were identified, analysed, and mitigations were initiated and follow up on. Many of the identified risks did not materialize in the project. However, some of the major risks that did materialize are outlined in the following Figure 2, which also summarise mitigation and status (State of Play) at the end of the project.

Risk	Description	Mitigation	State of Play
Supply Chain	Delay in producing the batch of ROSAs for testing. This step will be key for the demonstration and qualification steps, and to turn the ROSA into a product. We will use several test products for accelerated ageing tests, standard tests, and product refinement. So, a delay in the delivery of a batch of the test products can delay the projected enrolment. The work plan has been developed with as much parallelization as possible to prevent any delays in components and subsystems from delaying the rest of the project. Still, the semiconductor industry has been facing major delays and bottlenecks, so we need to consider this risk. The delay in delivering the batch of ROSAs for testing could delay all the subsequent steps of testing and qualification and thus delay our market entry.	We have selected several alternative partners (Argotech, Beckermus, Optech) for batch production that can quickly respond and fill the gap or failure of our production partner.	This risk of delay on the ROSA did indeed materialize during the project. We initially attempted to mitigate this by using two contract manufacturer, YouOpto and AVO. While we did manage to get and test ROSAs from YouOpto, these turned out to vary significantly in performance and we decided to prioritize the AVO approach, which involved a re-design to hopefully gain more consistency. However, this part was also further delayed due to failing housing from the housing sub-contractor, which meant we had - again - try to mitigate by sourcing the housing from three different housing vendors. Status is that we now have tested AVO bulk ROSAs using two of the housing vendors. The delay on the bulk ROSA meant that we did not reach to the Beta level on the bulk ROSA, as originally planned. Instead, we augmented our effort by developing a PIC-based ROSA, which now have caught up the bulk version, and will be the ROSA of choice going forward.
Technology Acceptance	Our technology differs considerably from market-leading approaches. Bifrost is a new entrant in the Access/5G market, and therefore we need to gain confidence from the key stakeholders in the sector. We will tackle this risk with the planned demonstration activities in the project. We are also aiming at different applications, with different customers/solutions within each market. We will maintain close contact with customers and vendors engaged in standardization. Failing to successfully demonstrate the benefits and performance of our technology and to convince key stakeholders (vendors and operators) would drastically jeopardize our market strategy and risk our business sustainability.	We have a strong engagement with several key players in the market that already know our technology and are closely following our development (Nokia, Ericsson, COX, Verizon). The engagement of those stakeholders in the process will consolidate the confidence in our solution and cement the reliability of our technology in the industry forefront.	While our receiver technology does differ from conventional direct-detection, the interface of our ROSA is build to integrate straight into a standard transceiver. Our involvement in various standardization bodies and our involvement with key players in the market appears to have paid off and it appears that our QC-technology can be accepted for as long as the above is true. Our introduction of a SFP transceiver - fully compliant with the standards - have created substantial interest in the market. This even for more conservative customer such as Ericsson, whom are highly supportive of us in the MOPA organization.
Competition	The ICT market evolves very quickly, and competitors are working hard on developing new solutions. Competitors may come up with new solutions that can somehow respond to the operators needs in terms of reach and bandwidth. This is a moderate risk, as our technology clearly surpasses competing solutions and we have already defined a technology roadmap to go up to 100 Gbps. Still, we will work on creating pull from operators to overcome competition. An accelerated market entrance, with the support of the EIC-Accelerator will also help to overcome this risk. The rise of solutions directly competing with Bifrost's QC-ROSA technology could significantly impact our sales.	Our uniqueness and IP-protected innovation, shield us from any close potential direct competitor. Much of the potential breakthrough developments in the field are still in the early stage of R&D, and we have a clear first-mover advantage over them. Furthermore, our roadmap already includes solutions up to 100 Gbps.	During the project period, we have indeed experience competitors launching new transceivers with higher reach and speed. Several of these have been with claims that have turned out to be optimistic. Companies such as Adva and Percision OT have claimed 25G over 40km. Both have turned out to be able to only reach about 30km. This has been commented on in the market by other players, and it is generally acknowledge that Bifrost is the only company that can truly reach 40 km at 25G with the types of transceivers used in the Access (SFP). Noone can reach 15 or 20 km at 50G, and we expect to have a unique position in the market once we have our 50G product launch.

Figure 2 Risks materialized during the project.

Aside from the delay due to the housing, we believe, we met and exceeded the milestones of the project.

5. Project results

ASIC Development

Our ASIC team has developed multiple configurations for 10, 25, and 50 Gbps. The latest results prove that we can reach 40 km at 25 Gbps. This can potentially be of interest to NG-PON2 as an upgrade path from 10 Gbps. It also has great potential for the DWDM networks used by many smaller/medium operators as well as cable operators, and we are in dialogue with several transceiver vendors for this application.

With our design of a 50 Gbps ASIC and PIC, we expect to be able to demonstrate a reach of 15 km in the C-band. This fulfills the strictest requirement set in the MOPA specification, and at this time it appears that it can only be achieved by Bifrost technology.

For the NG-PON2 application, the first tests were performed with a 25 Gbps ASIC. This has degraded the dynamic range to 14 dB instead of the required 20 dB. In addition, due to the broader high-pass input filter in the ASIC required for 25Gbps compared to 10Gbps, the input frequency range of 20 GHz is less than the 24 GHz required for burst mode operation. In the ASIC designed for PIC implementation, there is no high-pass filter due to the use of balanced photodetectors. This has increased the frequency response well beyond the burst mode requirements. Similarly, for the dynamic range, the PIC-ASIC combinations have shown more than 30 dB dynamic range, thus exceeding requirements by more than 10dB. We are therefore ready to launch a dedicated NG-PON2 capable PIC-ROSA if/when a market opportunity arises.

For the SSB for cable operators use case a balanced dispersion tolerance covering the range from -500ps/nm to +500ps/nm is required to cover the whole range 0-60 km when half-span dispersion compensation is used in the link. Our dedicated SSB ASIC (062) have demonstrated this with a receiver sensitivity better than -17 dBm from 30 km to +30 km, thus fulfilling the requirements. This ASIC is designed for bulk ROSA implementation with single-ended photodetectors and is not suitable for PIC implementation with balanced photo detectors.

The 25 Gbps ASIC (072) designed for PIC implementation covers both the mobile fronthaul and the cable operators use cases, with improved performance over ASIC 062 (dedicated for cable operators) and ASIC 068 (dedicated for Fronthaul) for both use cases.

Details of the NG-PON2 tests can be found in Appendix 1. Note that the PIC-ROSA performs beyond the highest NG-PON2 requirement (E2). Note also the PIC-ROSA can reach 120km at 10Gbps with only 4 dB penalty(!). This is exceptional performance – not even close to be matched by anyone else in the industry.

Test results for the Cable Operator use case can be found in Appendix 2. Note that this ASIC, designed for Bulk ROSA implementation, does meet the requirement for Cable Operator with reach 0-60km including 30km inline dispersion compensation as outline in this use case.

Test results for the Bulk-optic Fronthaul use case can be found in Appendix 3. Note that this ASIC, designed for Bulk ROSA implementation, does meet the requirement for Front-Haul with 40 km reach with performance level comparable to competition only reaching 15 km at 25 Gbps.

Overall, the results of the ASIC development exceeded expectations and demonstrated that all three use cases can be obtained in a Bulk ROSA implementation.

Further to this develop of ASICs for the Bulk ROSA, we also developed ASICs (and PICs) for a PIC ROSA, see Appendix 4. Test Result for this ASIC and Silicon Photonics PIC have shown excellent performance from 0 to 40km. This ASIC and PIC will be used in PIC ROSAs and SFP transceivers (see later in the report).

These results are record breaking and highly attractive for both Fronthaul and upgrades of DWDM networks for both Cable and Telecom Operators.

Bulk ROSA Development

A detailed test report of the Bulk ROSA from Youopto and first AVO units can be found in Appendix 5.

This ASIC (062) was mounted in 5 ROSA units by Youopto. All 5 failed due to excessive insertion loss leading to poor performance. ASIC 062 was not mounted in an AVO ROSA as it was superseded by the better performing 072 ROSA for PIC implementation that will work for both Mobile Fronthaul and the Cable Operators use cases. After the transition to PIC implementation, ASIC 068 has been replaced by ASIC 072.

Further results of the AVO Bulk ROSAs using First Opto and Kyocera housing can be found in Appendix 6 and 7.

Our conclusion to the Bulk ROSA development is that while it is possible to meet the objectives set out, it is very difficult to implement in reality as in a production setup where yield becomes a major factor. We do not believe we could reach a yield better than 50%, and it would require at least 90% to obtain an acceptable Cost of Goods Sold (COGS).

Since we have developed a PIC ROSA successfully, we will focus all our efforts on such. The Bulk ROSA has been a great steppingstone for our company, and we would not have been where we are today without this project.

PIC ROSA & SFP Transceiver Results

During the project, we entered into a collaboration with Estel for the development of a full transceiver. Estel has set up a fully automated transceiver production line in Belgium and is in the process of expanding. Estel also has design team, located in Sweden, with highly experienced transceiver designers. This collaboration has been very important to our launch of a transceiver that at specifically designed to meet the rigid requirement of the telecom operators. With Estel, we designed an SFP around our PIC ROSA as outlined in the following.

We have mounted ASIC 072 together with a Silicon Photonics PIC in PIC-ROSAs ready for mounting in our first SFP transceivers. The PIC ROSA replaces most of the internal optics in the bulk ROSA with a single Photonics Integrated Circuit that can be produced in high volume at very low cost. The PIC is wirebonded to ASICs specifically developed for those PICs.

The biggest challenge in the packaging of the PIC and ASIC into a ROSA lies in the optical coupling from the signal through a hermetically closed window and into the PIC. Suspended edge couplers are included in the PIC to facilitate better alignment tolerances. The optical coupling is performed by a 2-lens beam compression system that matches the optical mode of the fiber to the optical mode of the PIC waveguide. The LO used in the PIC ROSA is the same as the one used in the bulk ROSA.

We have received a total of 6 PIC-ROSA prototypes. The first 2 were combined with commercially available standard transmitter optical sub-assemblies (TOSAs) and mounted in SFP transceivers and used for live demonstrations at ECOC 2025 where 25 Gbps data was transmitted from one SFP over 40 km fiber and received error free by the other SFP. The demonstration ran continuously for several days and gathered extensive customer interest.

For the other 4 PIC-ROSA prototypes, 3 will be mounted in SFP transceivers and 1 will be retained in ROSA form for additional testing.

Regarding insertion loss and optical coupling efficiency, the first unit experienced nearly 10 dB insertion loss in the signal path. The contract manufacturer AVO quickly gathered experience in the assembly after this, and subsequent units showed strong improvements. The latest 4 units are all within specs and clearly outperform the bulk ROSAs. This showcases the robustness towards optical alignment in the PIC implementation and is very promising regarding high yield and low cost volume manufacture.

The first SFP has been subjected to power consumption vs temperature measurements. For C-temp (0 to +70 degrees) power consumption is below 2.5 W. Further tests are needed to ensure that power consumption is below the 3W target for the I-temp range -40 to +85 degrees

A walk-through of the development from PIC to SFP together with test results for the PIC-ROSAs and SFPs can be found in Appendix 8.

In summary, we made substantial technological advancement during the project. While the bulk-ROSAs were severely delayed and showed insufficient yield, we successfully developed silicon photonics PIC technology and packaging into PIC ROSAs. This development happened in record time – an achievement that was only possible due to the experience gathered through the bulk ROSA development. The advantage of the PIC ROSAs is heavily reduced component and assembly cost when moving into volume production. The PIC ROSA also provides a platform for straightforward upgrade to 50 Gbps and later 100 Gbps – efforts that have already started, and that would be extremely challenging in the bulk ROSA platform. When the PIC ROSA is taken into account, the technical results have exceeded the expectations.

We also developed a full transceiver in the SFP package. We intent to launch Pilot production of both PIC ROS and SFP shortly.

Commercial Results

Currently, we have substantial traction and interest from several major customers. We are targeting to build 50 units of our 25Gbps SFP in a Pilot production in Q1 2026. Some of these will be used for qualification according to Telecordia. About 25 units will be offered for sale to a limited number of interested customers. Juniper Network, Cisco, Ericsson, L2Tek, and I-Wave are all expected to place an order for a limited number of units for testing and trials. This will lead to orders of much larger volume, which we are in the process of preparing for through a financing round about to close. We expect to be able to produce volume of 1000 units per month in Q4 2026 and 5000 units per month in Q2 2027.

The target markets are very much in line with what we initially had outlined in the project (NG-PON2, Cable Operation Networks, Fronthaul). NG-PON2 is perhaps less, due to the fact that only Verizon really has implemented it on a large scale. That said, Verizon is interested in our 25 and 50Gbps solution as an upgrade path for NG-PON2, so there may still be possibilities for our technology in that market.

Some additional applications have emerged, that are perhaps caviats of the above, but where our QC technology has an advantage over competition.

Example 1 Next Generation Mobile Front Haul for 6G.

This is part of the MOPA specification, which Bifrost now is a member of and has a solution specifically for DWDM at 50Gbps per channel with reach up to 20km. The advantages of QC technology for this application are: Reach, no latency, low power consumption and SFP pluggable. Bifrost is the only vendor that can accommodate all of these requirements. While this is a longer-term market, the potential is enormous; millions of units needed by 2030. Technology is being selected now and can create short-term revenue as system integrators such as Ericsson will want to qualify products and pay for such.

Ericsson is highly interested in our 50Gbps solution for the next generation wireless fronthaul and has promoted our technology in the MOPA organizations and jointly written a technical solution using QC technology, which is now part of the MOPA specification. We expect this eventually will be included in future ITU and IEEE standards for mobile fronthaul.

Example 2 IP over DWDM

Router producers are seeking solutions for internet distribution bypassing the conventional Network switch. SFP DWDM 25Gbps pluggables with reach up to 40 km are desirable for this. Applications are similar to DWDM upgrades, but most likely many will be green fields.

Juniper and Cisco are highly interested in our 25G over 40km solution and are expected to place orders for test units by Q1 2026. Juniper has offered to showcase our solution with their router in their booth at OFC 2026.

Example 3 Real-time Video distribution of sporting events

This is coming as a very specific opportunity through L2Tek of the UK. The following comes directly from L2Tek:

The end user is ITV, who has obtained a single fiber connectivity service in London from BT Openreach with a primary route and a secondary route for resilience. The secondary backup fiber route is long ~30-40Km. The customer requirement is to transport a 12 Gbps uncompressed UHD video stream between two points with a primary and hot standby backup route.

The solution that they have arrived at in the near term is based upon Acacia QSFP 400G ZR which costs £6K per 400G transceiver -plus EDFA Amps and Mux Demux equipment to provision an 8 channel DWDM solution. They did look a lower cost PAM4 transceiver, but these required dispersion compensation in-line and thus were not considered as a practical solution. The overall solution hardware cost ~£50K for 1 X 12Gbps protected.

L2Tek would like to propose a trial of the Bifrost solution as a lower cost alternative to the end customer in the Q1/Q2 2026 timeframe. The idea would be to ask the ITV system integrator, Genesis to place a PO for test units of Bifrost SFP 25G 40 km reach for trial, with a view to Genesis then being able to offer a much more cost-effective solution in similar applications going forward.

L2Tek sees an opportunity to get a Video-optimised solution based on using Bifrost plugs working with Genesis for ITV via the BT OpenReach Fibre service and then take the solution directly to BT OpenReach and other customers in the UK.

EDGE AI

One “new” and rising application is an increasing need for IP distribution driven by Artificial Intelligence (AI), where the AI center is located near the edge. Edge AI is becoming a major market on its own and refers to the deployment of AI algorithms and AI models directly on local edge devices such as sensors or Internet of Things (IoT) devices, which require real-time data processing. Self-driving cars, wearable devices, security cameras and smart home appliances are among the technologies that use Edge AI capabilities.

Edge AI is estimated to be an USD 50B+ industry by 2030. A substantial part of this (about 50%) is from data distribution, requiring real-time data transmission with minimum latency.

The low or no latency specification is a unique feature of the Bifrost SFP pluggable. Given the longer reach without DSP, this can set us apart compared to full coherent in many cases. This has been recognized by several customers, including Juniper, Cisco L2Tek, and Ericsson.

Dissemination Activities

Major efforts on dissemination and customer engagement have been carried out. As part of our commercialization effort, we have hired three international Business Developer with industry experience. During the project our full client base evolved to more than 300 individual contact persons.

Website: A dedicated third-party expert supports website maintenance. Regular updates and graphics reflect project milestones. [www.bifrostcommunications.com]

Events and trade shows:

- OFC 2024 (San Diego): Demonstration showcased in Semtec’s booth; posters displayed at Sanmina’s booth.
- EPIC Meeting, FSAN Meeting, ECOC 2024: Bifrost participated to network and present developments.
- OFC 2025 April (San Francisco): For the first time we showcased a complete transceiver in our own booth launching the 25Gbps 40 km reach.
- ECOC 2025 September (Copenhagen): Bifrost exhibited our SFP transceiver in our own booth as part of the Danish Innovation Pavilion. A live demonstration over 40km using real data were exhibited at the Estel boot.

Collaborations and technology alliances:

- Estel – our SFP design house and contract manufacture
- Joint development with Pilot Photonics (tunable laser integration).
- PIC-based QC-ROSA co-developed with Fonex.
- Partnership with III-V Labs and Nokia via the 6G-EWOC project for 100 Gbps QC-ROSA including transmitter.

Standardisation forums:

- Member of MOPA (Mobile Optical Pluggable Alliance).
- Consultant member of FSAN (Full Services Access Network).

Newsletters and Media

- Periodic newsletters were sent to stakeholders with key updates.
- In connection with OFC 2025 in San Francisco, Bifrost posted 2 press releases. The press releases were shared with more than 80 different dedicated telecommunication media.

Materials Developed

- Handouts
- Datasheets
- <https://bifrostcommunications.com/applications/>
- <https://bifrostcommunications.com/documentation/>
- <https://bifrostcommunications.com/bifrost-launches-dsp-free-qc-transceiver-for-25-gbps-and-40-km-reach/>

6. Utilisation of project results

Bifrost is a private company with a commercial interest in developing, producing and selling a product. The company is based on several inventions protected by multiple patents families in several countries. The industry of telecom and data transport is a mature industry with established standards and rigorous qualifications of new products. As such, one can only be successful if one can repeat the result in multiples. A startup company introducing a new technology to an established industry it is necessary to be open about our science. Our communication and dissemination happen primarily through industry channels, such as organizations for (new) standards, and at trade shows. As part of this we make public announcements of the results through the media of the industry. Example is our latest announcement for ECOC 2025, of our 25Gbps, 40 km SFP, which was submitted to more than 80 media. Another relevant aspect of keeping an open science is the fact, that we want the industry to adapt our technology, as in, we are happy to enter in to licensing of our technology to other companies wanting to build their own version of QC-based transceivers.

Product Offering and Road Map

The product road map can be is outlined in Figure 3.

Product Roadmap - Complete Transceivers	Product Availability					
	Fixed	Tunable	2026	2027	2028	2029
25 Gbps 40 km Reach QC-NRZ	x					
25 Gbps 40 km Reach QC-NRZ		x				
25 Gbps 60 km Reach QC-NRZ	x	x				
25 Gbps 80 km Reach QC-NRZ	x	x				
50 Gbps 20 km Reach QC-PAM4	x					
50 Gbps 20 km Reach QC-PAM4		x				
50 Gbps 40 km Reach QC-PAM4	x	x				
100 Gbps 20 km Reach QC-PAM4	x	x				

Figure 3 Product Road Map

Aside from the SFP product portfolio, Bifrost also offers the ROSA, the ASIC, the PIC, and a straight license to the QC technology to those transceiver vendors desiring to take advantage of our technology.

Production Ramp Up and Revenue

Bifrost is planning to ramp up production over a period of 2 years to reach a monthly volume of approx. 10K SFP units per month by 2028.

First revenue is expected in Q1 2026. Our business case indicates revenues in the DKK 100Ms by 2029.

Funding and Investors

Investors: during the period we have raised approx. DKK 40 M from private investors. We also obtained an EU grant of DKK 18,5M from the EIC Accelerator, with blended financing allowing the EIC Fund to invest directly in Bifrost, which they have as part of the above. We are about to close on an additional round of DKK 18M from current investors including EIC Fund. We plan to go for a series A investment in 2026 following commercial success on our SFP launch.

Competition

In the market for SFP 25G at longer reach there are a few competitors that need to be followed and considered.

Adtran is offering a tunable SFP 25G with a claimed reach of 40km. They have obtained this by using PAM4. This solution will have higher power consumption than ours and it will introduce some latency as well.

Precision Optics is offering a tunable SFP 25G with claimed 40km, which they obtain by using a special ASIC to introduce SSB on the transmit side. This solution will have less receiver sensitivity than the Bifrost solution.

Point2 is offering a Clock and Data recovery with a DSP that can correct for dispersion. They claim reach of 40km, but we know from several customer, who have compared this to our solution that they can only reach

about 30km unless they use an external modulator. There are transceiver vendors utilizing the Point2 ASIC for high end transceivers. The DSP will further introduce latency.

In the Market for SFP 50G, we are not aware of anyone even close to reaching 15 km.

Market Entry

A major consideration for Market entry is the fact that Bifrost is a new entrant in an industry, which is quite conservative. To overcome this, we have engaged heavily in standardization work, giving us direct access to customer and partners deeply involved in shaping the next standards of the industry. While our receiver technology does differ from conventional direct-detection, the interface of our ROSA is built to integrate straight into a standard transceiver. Our involvement in various standardization bodies and our involvement with key players in the market appears to have paid off and it appears that our QC-technology can be accepted for as long as the above is true. Our introduction of a SFP transceiver - fully compliant with the standards - have created substantial interest in the market. This even for more conservative customer such as Ericsson, who are highly supportive of us in the MOPA organization.

Intellectual Property (IP) Management

Bifrost Communications owns 6 patent families all at various stages. All have been granted at minimum in one country. During the project, extensive IP effort has been undertaken to obtain protections in many countries. In addition, 2 new patent applications were filed during the project.

Regulatory Compliance and Standardization

Bifrost Communications executives are highly active in the forums for standardization. This involves the participation in meeting for NG-PON2, FSAN, and latest MOPA. This effort is highly important as it serves to ensure our product is compliant with existing and future standards in the industry. Certification activities are expected to commence once first Pilot production starts. Dialog with Estel and Baltic to perform certification testing has started.

International Expansion

This is a B2B business. At this point in time, most customers can be served from our headquarter in Denmark and by traveling to the customers for demonstration and commercial discussions. As a first start on an international expansion, we are currently looking for internal sales executives and expect to have such hired or engaged by during the remaining project period. As the product becomes qualified and commercial contracts emerges, we expect to set up sales and customer service centers in other countries in Europe and North America.

Expected Impact on Future Energy Consumption

The project has resulted in the maturation of the QC technology to a point where transceivers are now available in the SFP format, desired by most Operators. This allows for the build of internet data distribution networks

using far less energy due to the fact that regeneration point can be further apart by a factor of 2-3. This, in turn, means the number of Central Offices covering a specific area can be reduced by a factor of 4-9, yielding a reduction in power consumption of up to 90%. On a global scale, our technology could reduce the energy consumption of the Access Network by 50%, translating into a 30% energy reduction in the Internet industry.

7. Project conclusion and perspective

The original aim of the project was to develop a Bulk ROSA utilizing quasi coherent technology. This was done with more than 24 months delay due to substantial delays on the housing. The Bulk ROSA turned out to be very difficult to produce in volume due to optical alignment issues. As an alternative, we developed a ROSA based on Photonic Integrated Circuit (PIC), which turned out to be superior to the Bulk implementation. Further, we developed a SFP transceiver using the PIC ROSA. The SFP/PIC ROSA can fulfil all of the objective set out in the project, and it can be produced in volume.

Next step is to set up a Pilot production of both the PIC ROSA and the SFP and gain commercial traction. Further ramp toward volume production is planned as well.

Future development includes higher speed at 50Gbps and 100Gbps with longer reach than what can be achieved with Direct-Detection, yet still in the SFP form factor. A product roadmap has been outlined including both 50Gbps and 100Gbps at reaches that are unprecedented in the industry, setting the company ahead of competition. This technology provides an attractive alternative to full coherent, which is expensive, power hungry and has significant latency.

We believe that QC technology offers a unique opportunity to reduce the power consumption of the internet. We also believe this can be done while being commercially attractive to the end user/Operator.

8. Appendices

- Appendix 1 NG-PON2 Use Case
- Appendix 2 Cable Operator Use Case
- Appendix 3 Front Haul Use Case
- Appendix 4 PIC for Fronthaul and Operators
- Appendix 5 Bulk ROSA test report
- Appendix 6 AVO Bulk ROSA First Opto
- Appendix 7 AVO Bulk ROSA Kyocera
- Appendix 8 From PIC Test Board to SFP

Links:

<https://bifrostcommunications.com/applications/>

<https://bifrostcommunications.com/documentation/>

<https://bifrostcommunications.com/bifrost-launches-dsp-free-qc-transceiver-for-25-gbps-and-40-km-reach/>

https://www.linkedin.com/posts/e-s-tel_a-look-back-at-ecoc-exhibition-one-of-the-activity-7379846273518186496-kssN?utm_source=share&utm_medium=member_desktop&rcm=ACoAAAAra78B0hYD-zf1U5TXtjMYqYUVEEjXY1U

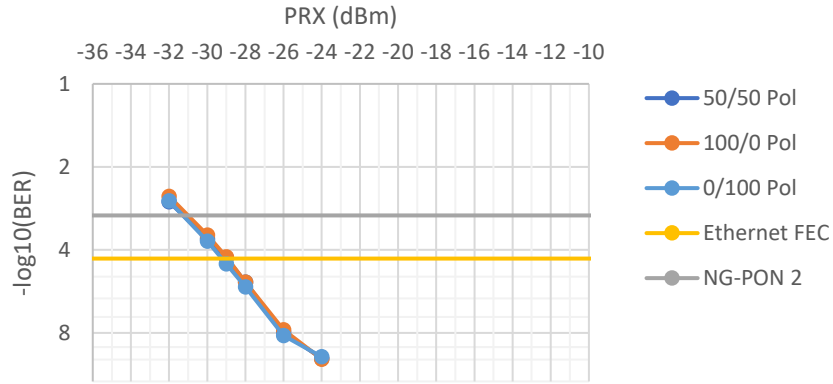
https://www.linkedin.com/posts/jesper-bevensee-jensen-777a60a_dsp-free-quasi-coherent-qc-sfps-are-here-activity-7376638832148025344-Te7?utm_source=share&utm_medium=member_desktop&rcm=ACoAAAAra78B0hYD-zf1U5TXtjMYqYUVEEjXY1U

Appendix 1

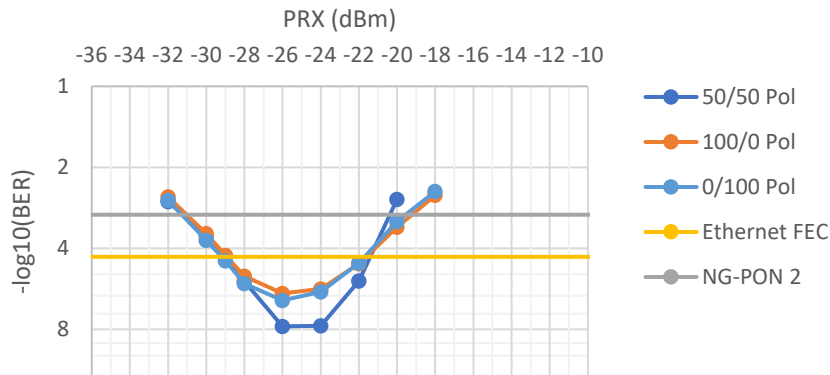
NG-PON2 Use Case Tests of ROSAs

Sensitivity curve for BTB

BTB



BTB



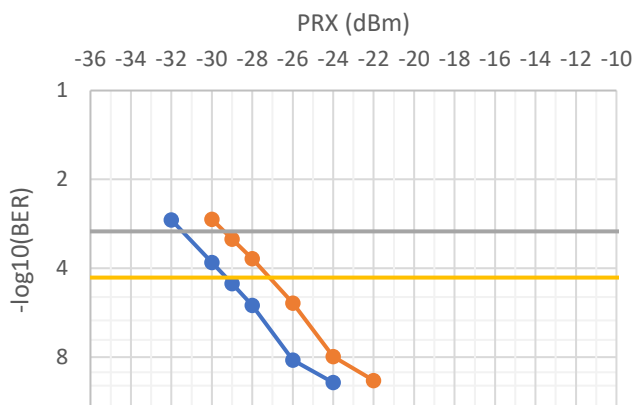
Parameter	Value	Sensitivity	PRX@ 1E-3 (dBm)
LO power (GUI)	14.5 dBm	BTB-100/0 Pol	-31
LO power(input)	9 dBm	BTB-0/100 Pol	-31.2
LO Wavelength	1548.45 nm	BTB-50/50 Pol	-31.2
Signal Wavelength	1548.91 nm		
Optimum IF	-27 GHz		
Vg1	Variable		
Slicing level	Variable, but around 0 crossing		
CTLE	Fixed for each curve		

Parameter	Value	Fiber distance	Sensitivity-PRX@ 1E-3 (dBm)
LO power (GUI)	14.5 dBm	BTB-100/0 Pol	-31
LO power(input)	9 dBm	BTB-0/100 Pol	-31.2
LO Wavelength	1548.45 nm	BTB-50/50 Pol	-31.2
Signal Wavelength	1548.91 nm		
Optimum IF	-27 GHz		
Vg1	2.75 V		
Slicing level	11		
CTLE	3 dB		

Fiber distance	Dynamic range (dB)
BTB-100/0 Pol	14
BTB-0/100 Pol	14
BTB-50/50 Pol	12

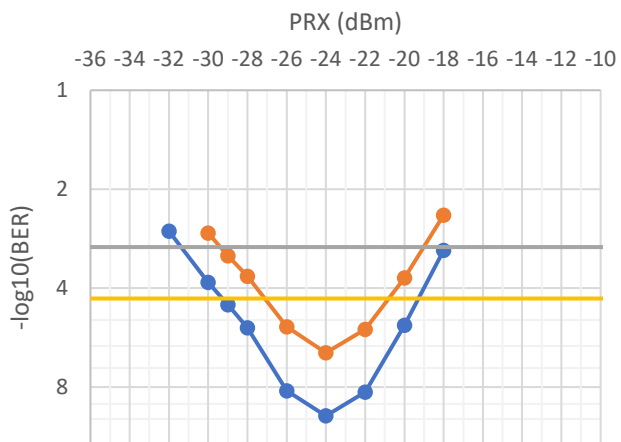
Sensitivity curve for 40 Km

40 Km



- Best Pol
- Worst Pol
- Ethernet FEC
- NG-PON 2

40 Km



- Best Pol
- Worst Pol
- Ethernet FEC
- NG-PON 2

Parameter	Value
LO power (GUI)	14.5 dBm
LO power(input)	9 dBm
LO Wavelength	1548.45 nm
Signal Wavelength	1548.91 nm
Optimum IF	-20 GHz
Vg1	Variable
Slicing level	Variable, but around 0 crossing
CTLE	Fixed for each curve

Fiber distance	Sensitivity-PRX@ 1E-3 (dBm)
40 Km-Best Pol	-31.5
40 Km-Worst Pol	-29.5

Parameter	Value
LO power (GUI)	14.5 dBm
LO power(input)	9 dBm
LO Wavelength	1548.45 nm
Signal Wavelength	1548.91 nm
Optimum IF	-20 GHz
Vg1	2.75 V
Slicing level	20
CTLE	1 dB

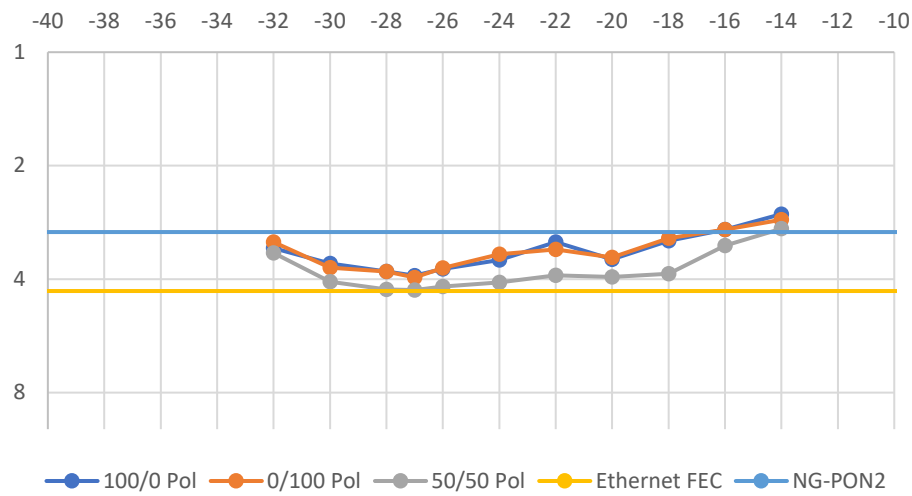
Fiber distance	Sensitivity-PRX@ 1E-3 (dBm)
40 Km-Best Pol	-31.5
40 Km-Worst Pol	-29.5

Fiber distance	Dynamic range (dB)
40 Km-Best Pol	14
40 Km-Worst Pol	12

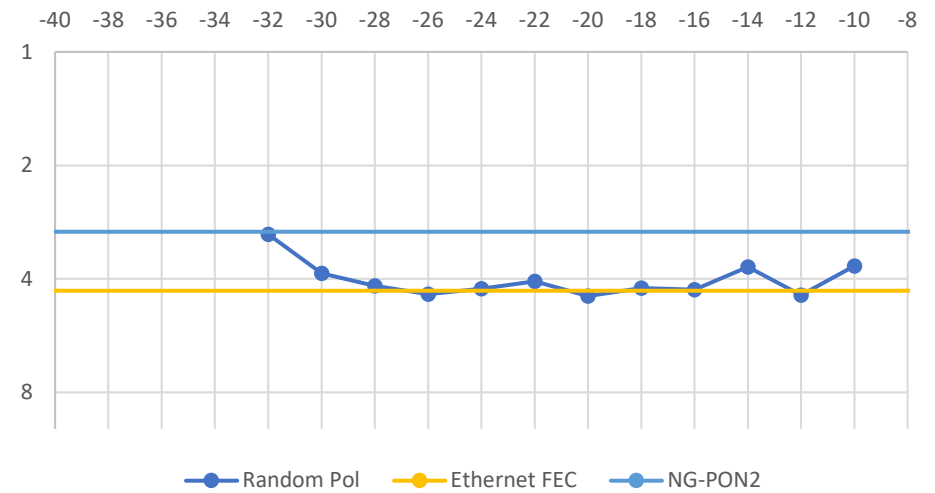
BER vs IF sweep

Parameter	Value
LO power (GUI)	14.5 dBm
LO power (input)	9 dBm
LO Wavelength	1548.45 nm
Signal Power	-29 dBm
Signal Wavelength	1548.91 nm

BTB

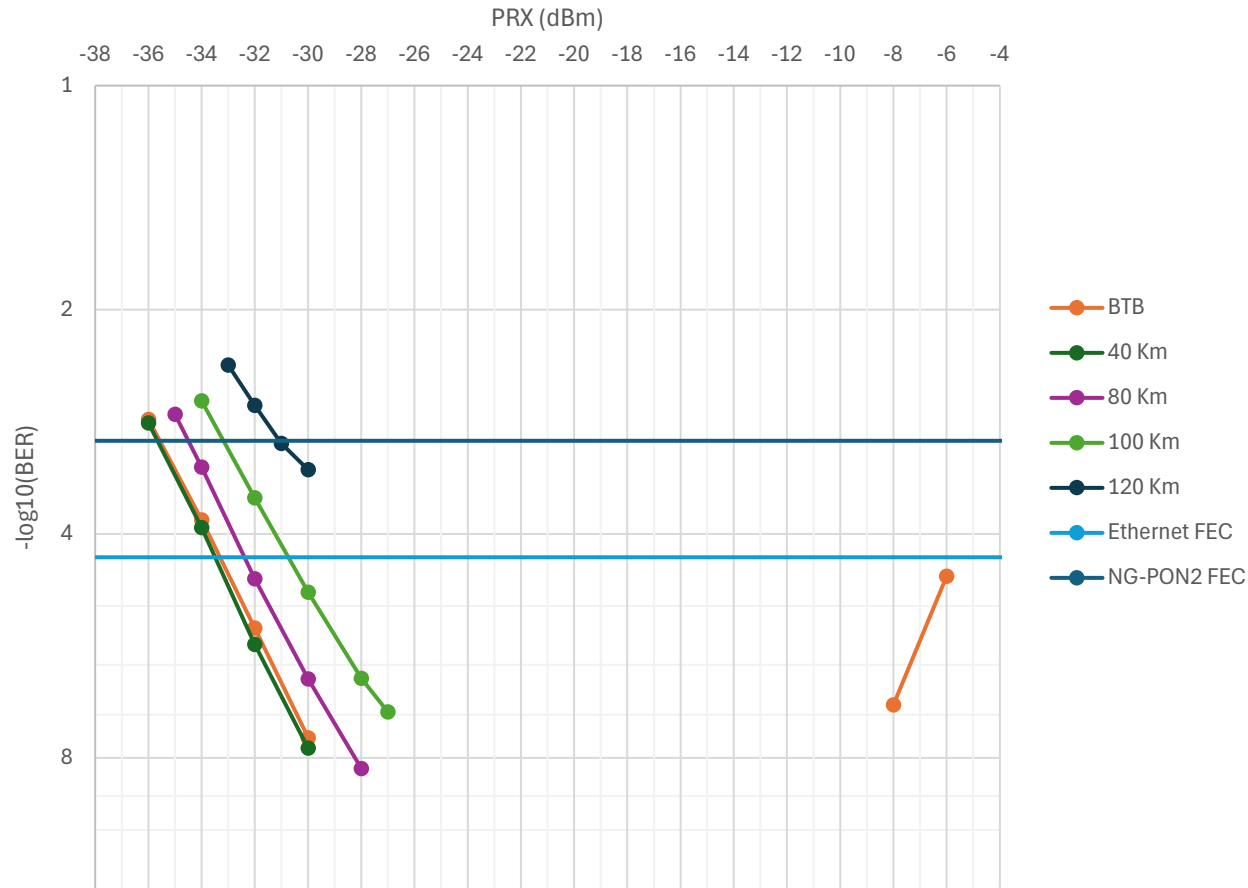


40 Km



PIC Implementation for NG-PON2 – Sensitivity results @ 10 Gbps

EV_TROSA0024_PIC3072 (10G)



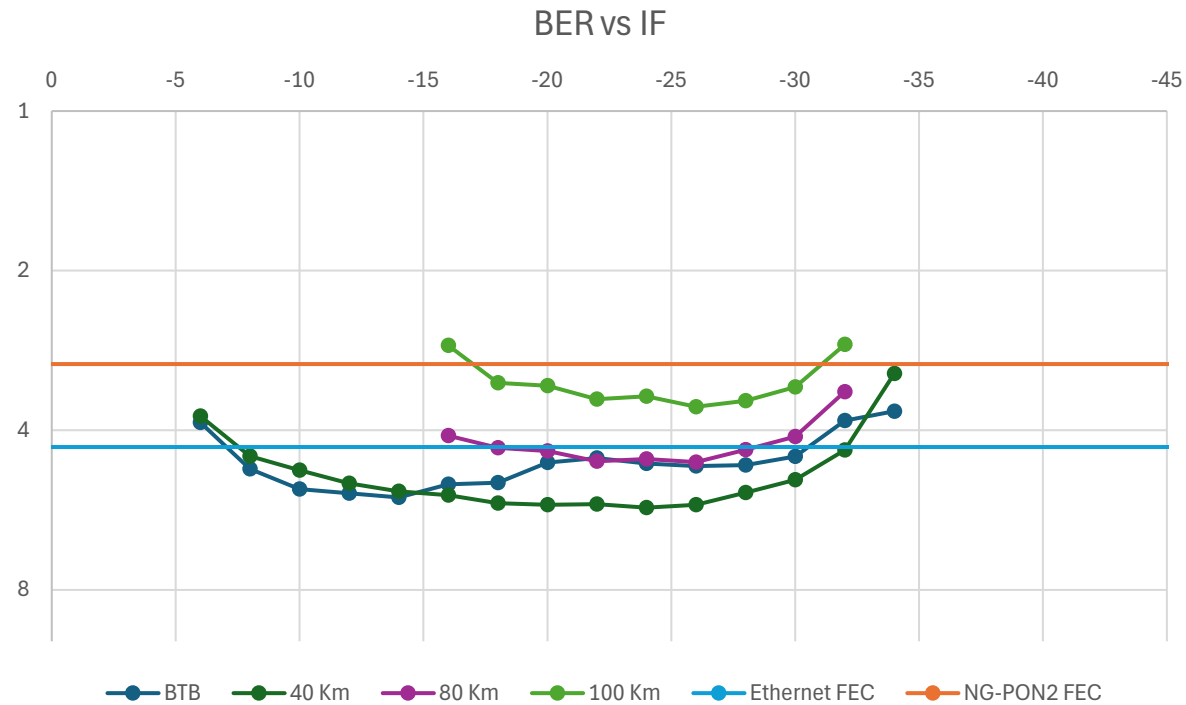
Dynamic range - 30 dB

Parameter	Value
LO power	10 dBm
LO Wavelength	1548.91 nm
Signal Wavelength	1548.91 nm
Optimum IF (BTB)	-16 GHz
Optimum IF (40 Km)	-24 GHz
Gain	Automatic gain control
Slicing level	Variable, but around 0 crossing
CTLE	Fixed for each curve

Sensitivity	PRX@ 1E-3 (dBm)
BTB	-35.6
40 Km	-35.7
80 Km	-34.5
100 Km	-33
120 Km	-31

BER vs IF sweep

Parameter	Value
LO power	10 dBm
LO Wavelength	1548.91 nm
Signal Power	-32 dBm
Signal Wavelength	1548.91 nm



Summary and Conclusion

Bulk Optics NG-PON2 Tests at 10Gbps :

- - 31 dBm sensitivity (required for class N2) demonstrated
(note: on par with best State-of-the-art NG-PON2 Receiver)
- Dynamic range is 12 to 14 dB depending on polarization. Requirement is 20 dB
- Frequency window measured is approximately 20 GHz. 24 GHz is required for burst mode
- These results were achieved with an ASIC that is not optimized for burst mode and are better than expected

Improvement for PIC implementation with dedicated ASIC:

- 5 dB expected improvement in sensitivity, so better than class E2
- +10 GHz improvement in frequency window due to higher PIC PD bandwidth, so better than burst mode requirements
- Improved gain control in dedicated ASIC improves dynamic range to 30 dB, which is 10 dB better than burst mode requirement
- In addition, the PIC-ASIC configuration have been tested at 80 km, 100 km and 120 km km. The result is highly impressive with only 1 dB penalty at 80 km and -31 dBm sensitivity after 120 km



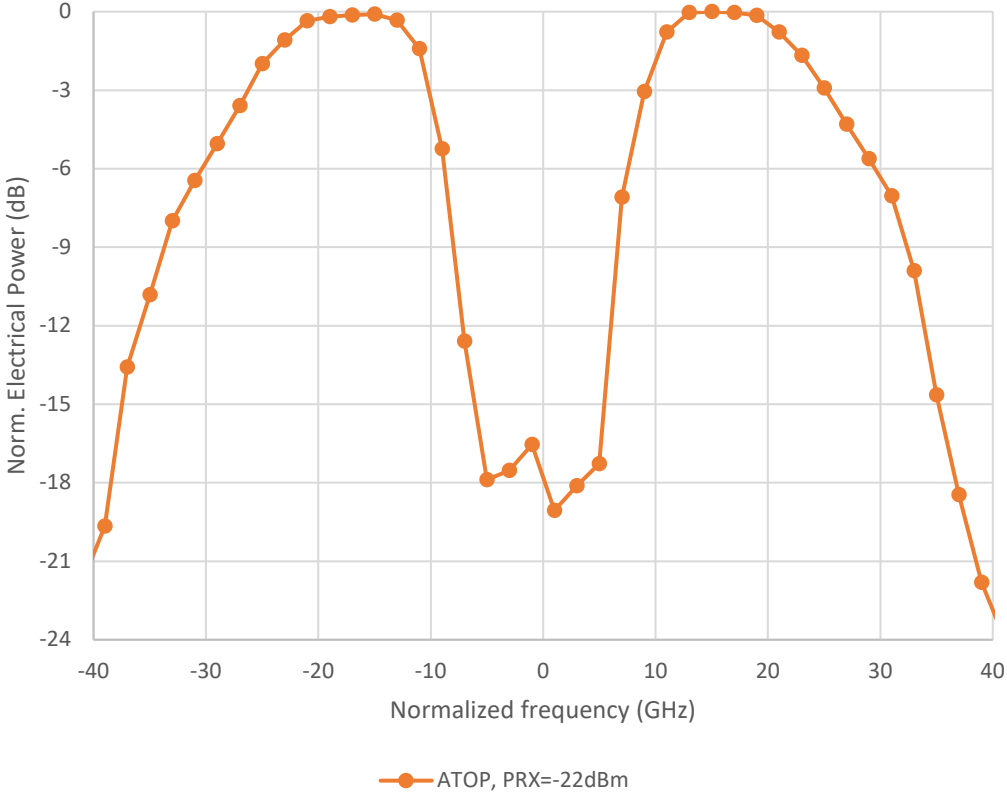
Appendix 2 Cable Operator Use Case
ASIC 062 with SSB test report

Description

	EV_0253-EV_0257
Board	PC_0013Rev1
PD	CPC5012S
TIA	CD25_062
ED	
TX	ATOP
CDR	Semtech GN2146

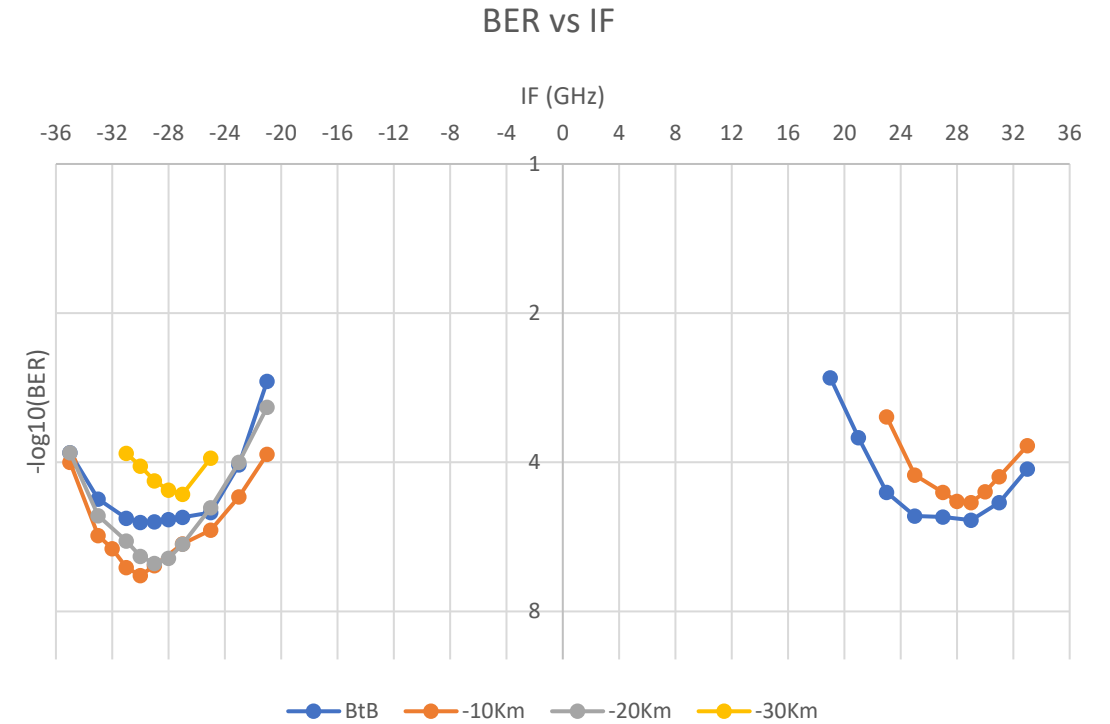
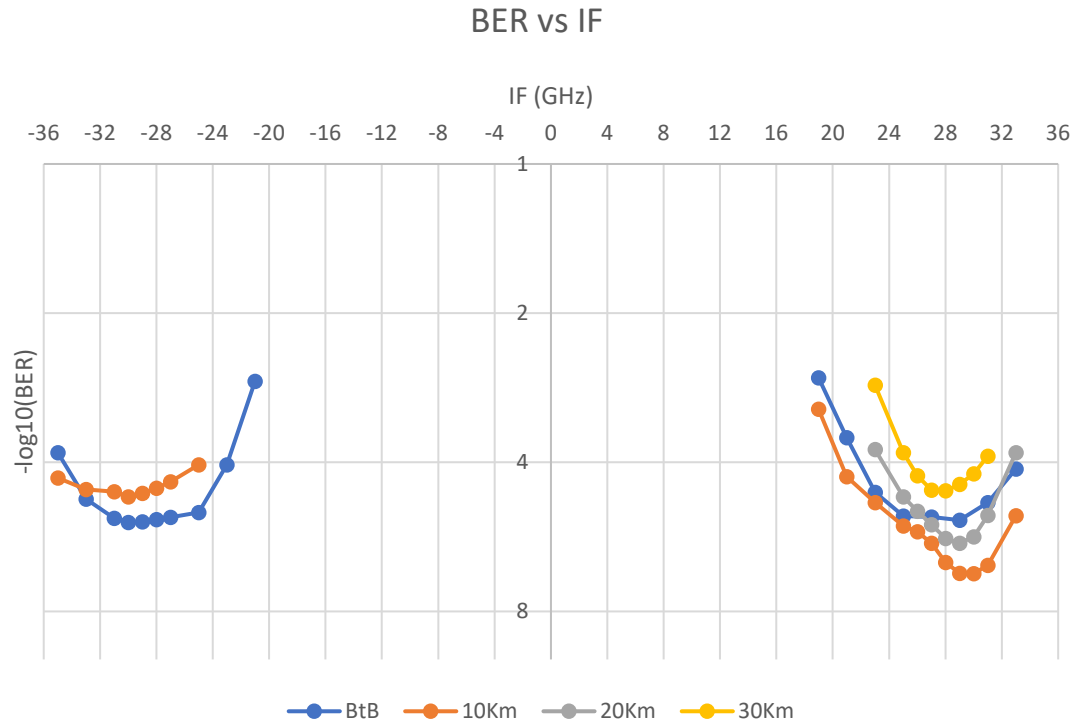
Frequency sweep curve

Parameter	Value
PLO (GUI)	10.3 dBm
PLO (input)	6 dBm
λ_{LO}	1550.92 nm
Vg1	3.3V
Vg2	2.6V



- Only one input was measured, Channel 2, since it has been done previously with AOI transceiver and both inputs showed the same response
- More curves were done to ensure that this wasn't saturated

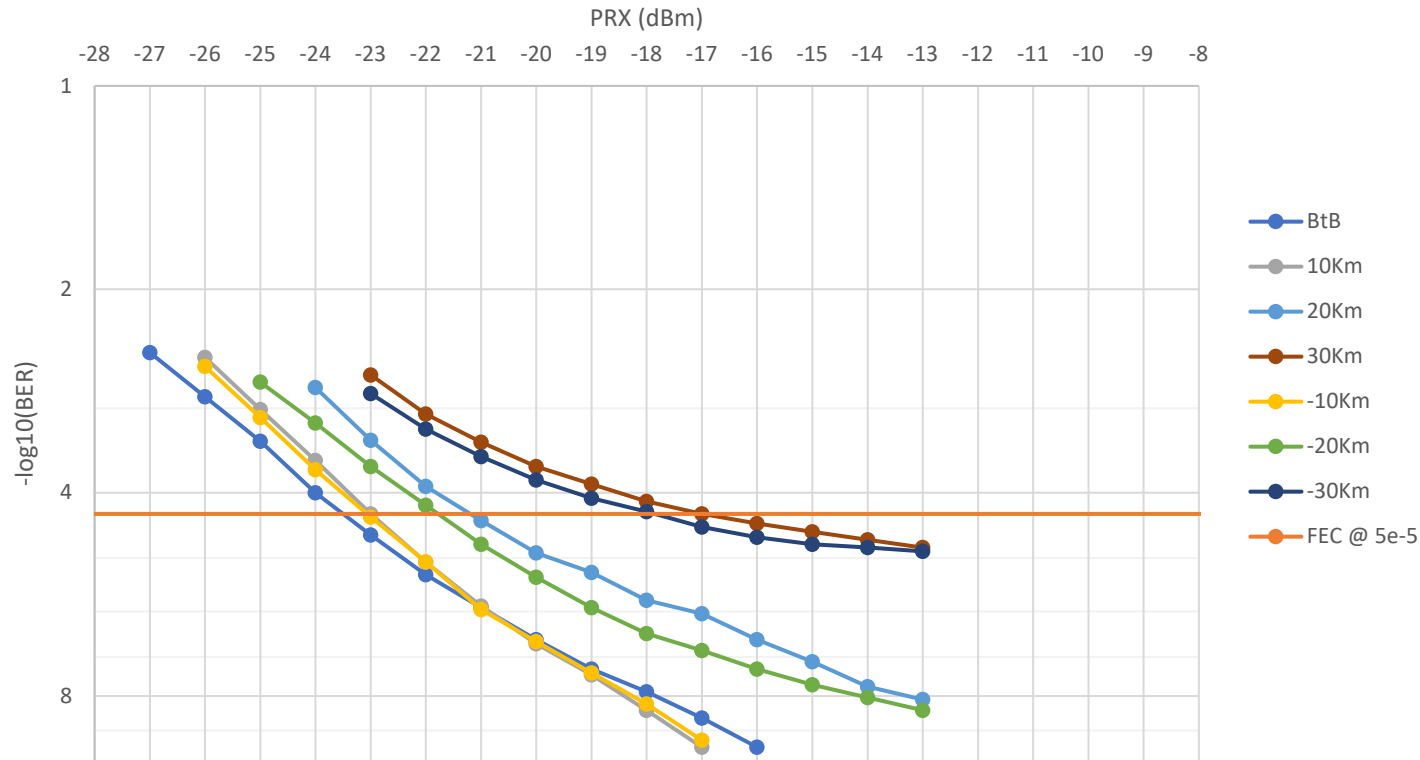
BER vs. IF curve



- The curves obtained are symmetric when looking at the negative and positive distance results
- In both cases, when increasing the distance, the optimum IF moves slightly towards lower frequencies

Sensitivity curve

Sensitivity with 6dBm LO



Parameter	Value
PLO (GUI)	10.3 dBm
PLO (input)	6 dBm
λ_{LO}	1550.92 nm
Vg1	3.3V
Vg2	Variable
Slicing level	Variable, but around 0 crossing
CTLE	Fixed for each curve

Sensitivity	PRX @ 5e-5
BTB (-30GHz)	-23.5 dBm
10Km (32GHz)	-23 dBm
20Km (31GHz)	-21.2 dBm
30km (30GHz)	-17 dBm
-10Km (-32GHz)	-23 dBm
-20Km (-31GHz)	-21.8 dBm
-30km (-29GHz)	-17.9 dBm

Summary and Conclusion

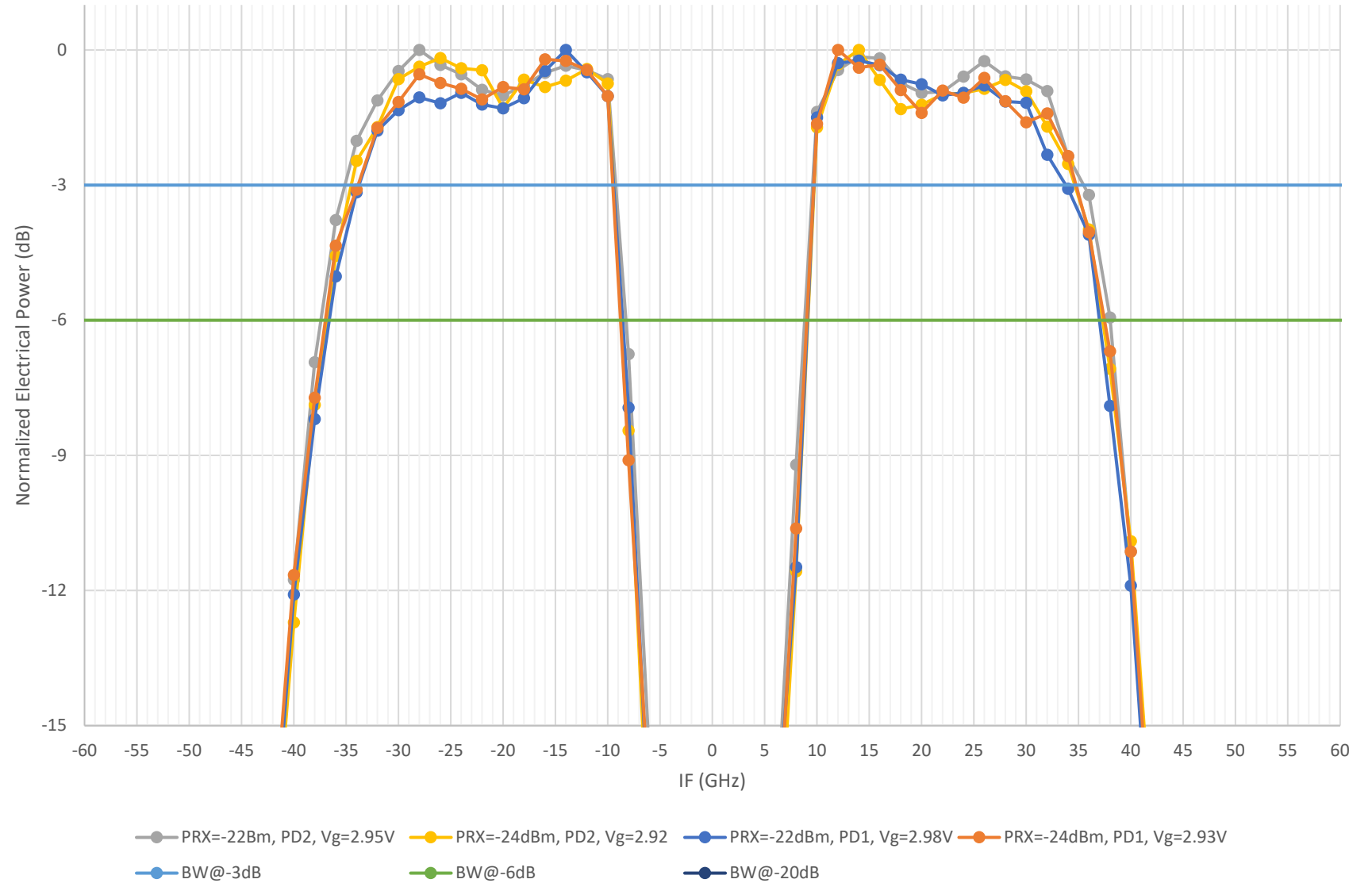
- The SSB ASIC for the cable operator use case have been tested against the +/- 30 km transmission requirements
- For back-to-back and +/- 10 km transmission, receiver sensitivity is better than -23 dBm
- For +/- 20 km transmission, receiver sensitivity is better than -21 dBm
- For +/- 30 km transmission, receiver sensitivity is better than -17 dBm
- All cases are better than requirement specifications
- This ASIC is designed for bulk-ROSA implementation - it has been superseded by the better performing ASIC 072 designed for PIC implementation



Appendix 3 Fronthaul Use Case
ASIC 068 test report

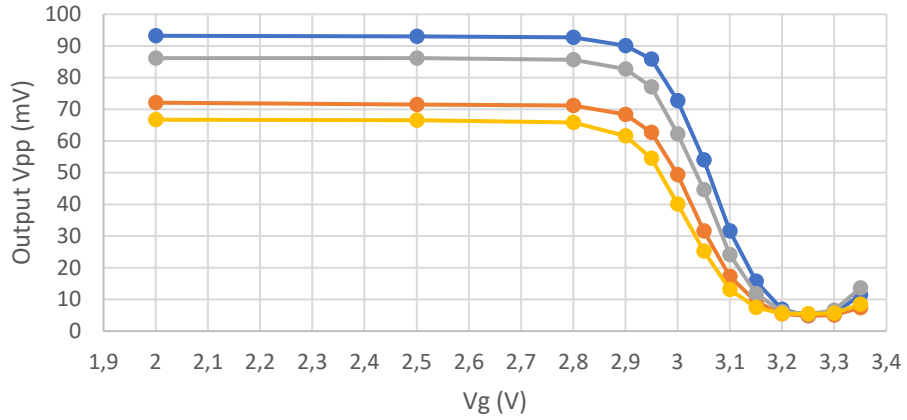
Frequency Sweep

Parameter	Value
PLO (GUI)	11.4 dBm
PLO (input)	6 dBm
λ_{LO}	1550.92 nm
VCC	3.3V
Current consumption	158 mA
Vg1 & Vg2	Variable



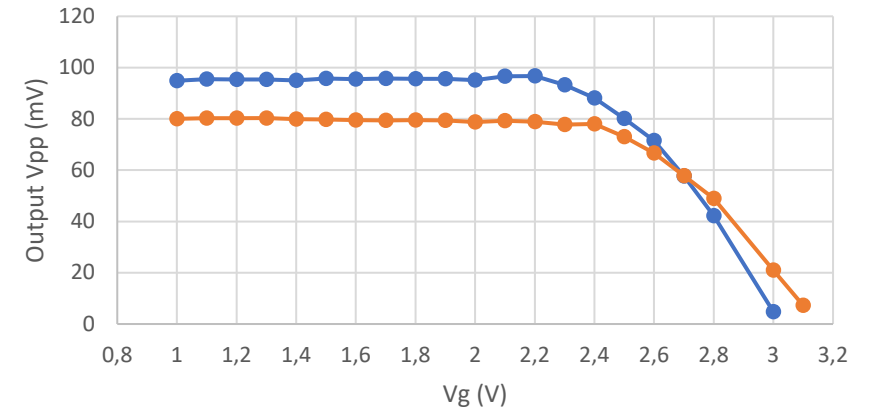
Dependence of eye amplitude on V_{gc}

Manual Gain Control



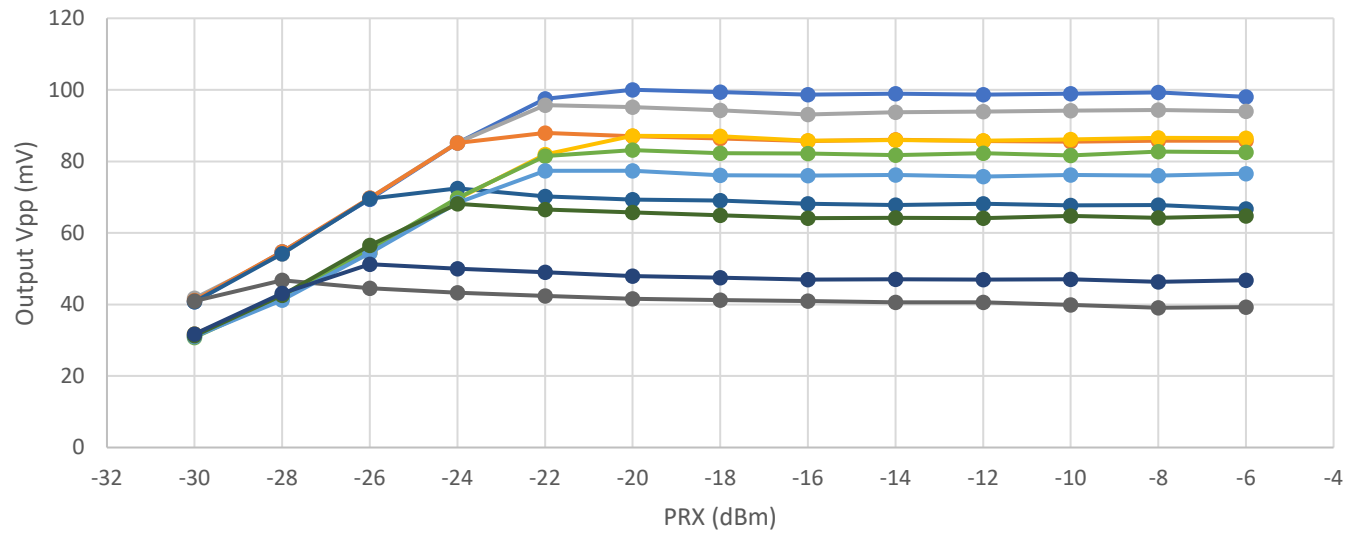
- PD2, PRX=-20dBm, IF = -25 GHz
- PD2, PRX=-20dBm, IF= -38 GHz
- PD1, PRX=-20dBm, IF=-25 GHz
- PD1, PRX=-20dBm, IF=-38 GHz

AGC, output Vpp vs. gain value



- PD2, PRX=-20dBm, IF= -25 GHz
- PD1, PRX=-20dBm, IF=-25 GHz

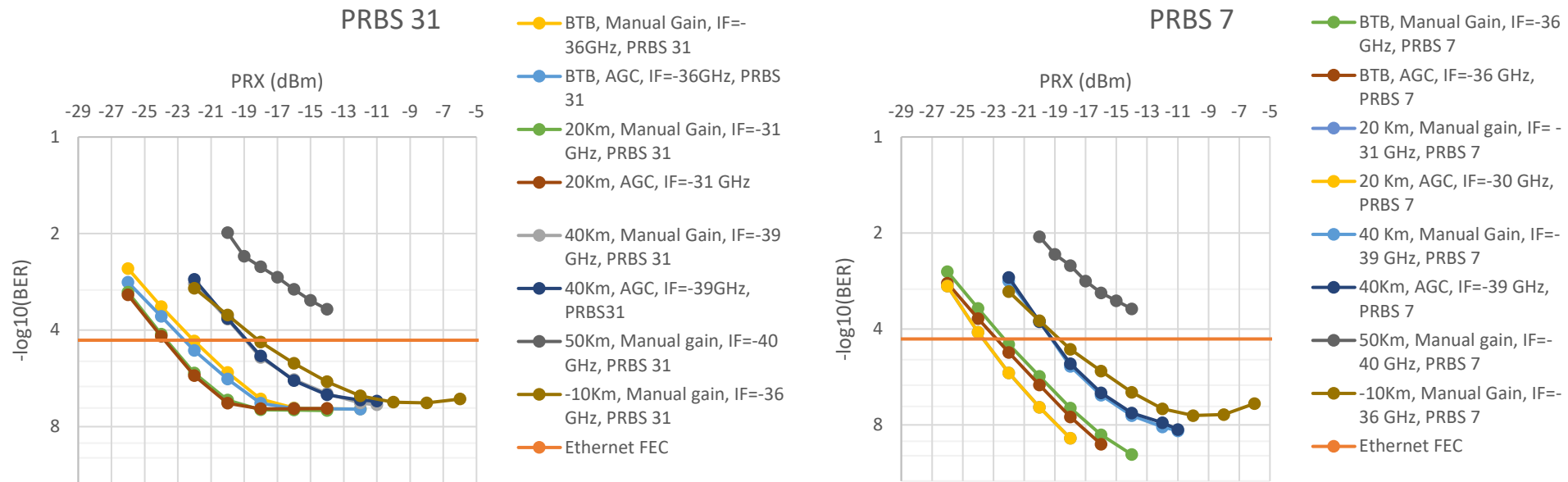
AGC, output Vpp vs. PRX



- PD2, Vg2=2.1V
- PD2, Vg2=2.25V
- PD2, Vg2=2.4V
- PD2, Vg2=2.6V
- PD2, Vg2=2.8V
- PD1, Vg1=2.1V
- PD1, Vg1=2.25V
- PD1, Vg1=2.4V
- PD1, Vg1=2.6V
- PD1, Vg1=2.8V

Sensitivity curve

- The Bifrost ASIC CD25_068 exhibits around 1.5-2 dB of improvement for 20 km transmission in comparison with BTB. 40 Km was achieved for this ASIC with a penalty of around 4 dB in comparison with BTB. Additionally, the manual gain control and automatic gain control (AGC) for all distances had a similar performance.
- Furthermore, 50 km was achieved as well but with a performance bit away from the FEC limit.



Sensitivity (Manual gain & AGC)	PRX @ 5e-5 (Ethernet FEC)
BTB	-22 dBm, -22.5 dBm
20Km	-23.7 dBm, -23.8 dBm
40km	-18.8 dBm, -18.9 dBm
-10 Km	-18.2 dBm

Penalty	Penalty @ 5e-5 (Ethernet FEC)
20Km	1.5 dBm
40km	3.5 dBm
-10Km	4 dBm

- In case of PRBS 31 all the cases have an error floor almost at the same point, but in the case of PRBS 7, both BTB and 20Km does not have error floor. However, it is important to note that the sensitivity almost remains the same for all cases.

Summary and Conclusion

- 40 km SSMF transmission has been demonstrated with a sensitivity of -18.8 dBm
- The penalty vs. B2B is 4 dB
- The ASIC was also tested for -10 km and 50 km. For -10 km, sensitivity is -18.2 dBm. For 50 km, the loss of the fiber was too high to achieve the required bit-error-ratio (BER) limit. Nevertheless, the ability to measure BER at both -10 km and 50 km demonstrates the robustness of the ASIC
- The automatic gain control (AGC) and the LO wavelength control systems in this ASIC have also been tested. Both systems work as expected and have been carried over to ASIC 072 for PIC implementation
- ASIC 068 is designed for bulk optics implementation and demonstrates its capability for use in DWDM Front Haul.

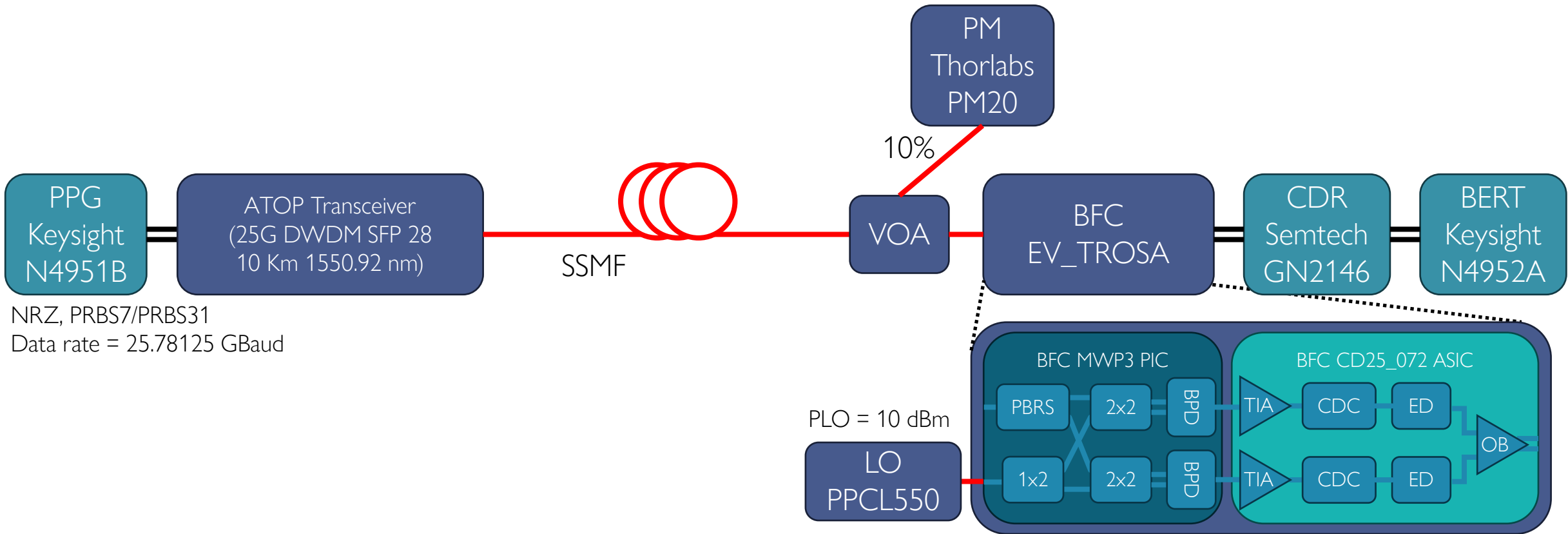


Appendix 4
PIC for Fronthaul and Operators

Introduction

- The report presents the results from measurements performed with the latest batch of four BFC MPW3 PICs with 072 ASIC for 25.78125 GBaud NRZ measured from 0 – 40 Km.
- Outline:
 - **BER Experimental setup:** Experimental setup for measuring the BER vs received optical power (PRX) with the parameters used for the measurements.
 - **Summary of Results:** summarization of the results for four different boards with two different PDs each (PD 28 & PD80). The results contain the combined bandwidth of the receiver, the excess insertion losses and the sensitivity for distances 0 Km, 20 Km and 40 Km.
 - **Comparison of sensitivity:** Graph of sensitivity to analyze the consistency of sensitivity for the different boards for distances 0 Km, 20 Km and 40 Km.
 - **MGC vs AGC:** Comparison of sensitivity results for one of the boards with manual gain control operation mode and automatic gain control operation mode.
 - **Range of working IF from 0-40 Km:** Local oscillator detuning tolerance with one of the boards under manual gain control and automatic gain control operation mode.

BER Experimental setup



NRZ, PRBS7/PRBS31
Data rate = 25.78125 GBaud

ASIC	Application Specific Integrated Circuit
TIA	Transimpedance amplifier
CDC	Chromatic dispersion compensation
ED	Envelope detector
OB	Output buffer

PIC	Photonic Integrated Circuit
PBRS	Polarization beam rotator and splitter
1x2	1x2 splitter
2x2	2x2 coupler
BPD	Balanced photodiode (PD)

BER Experimental setup description

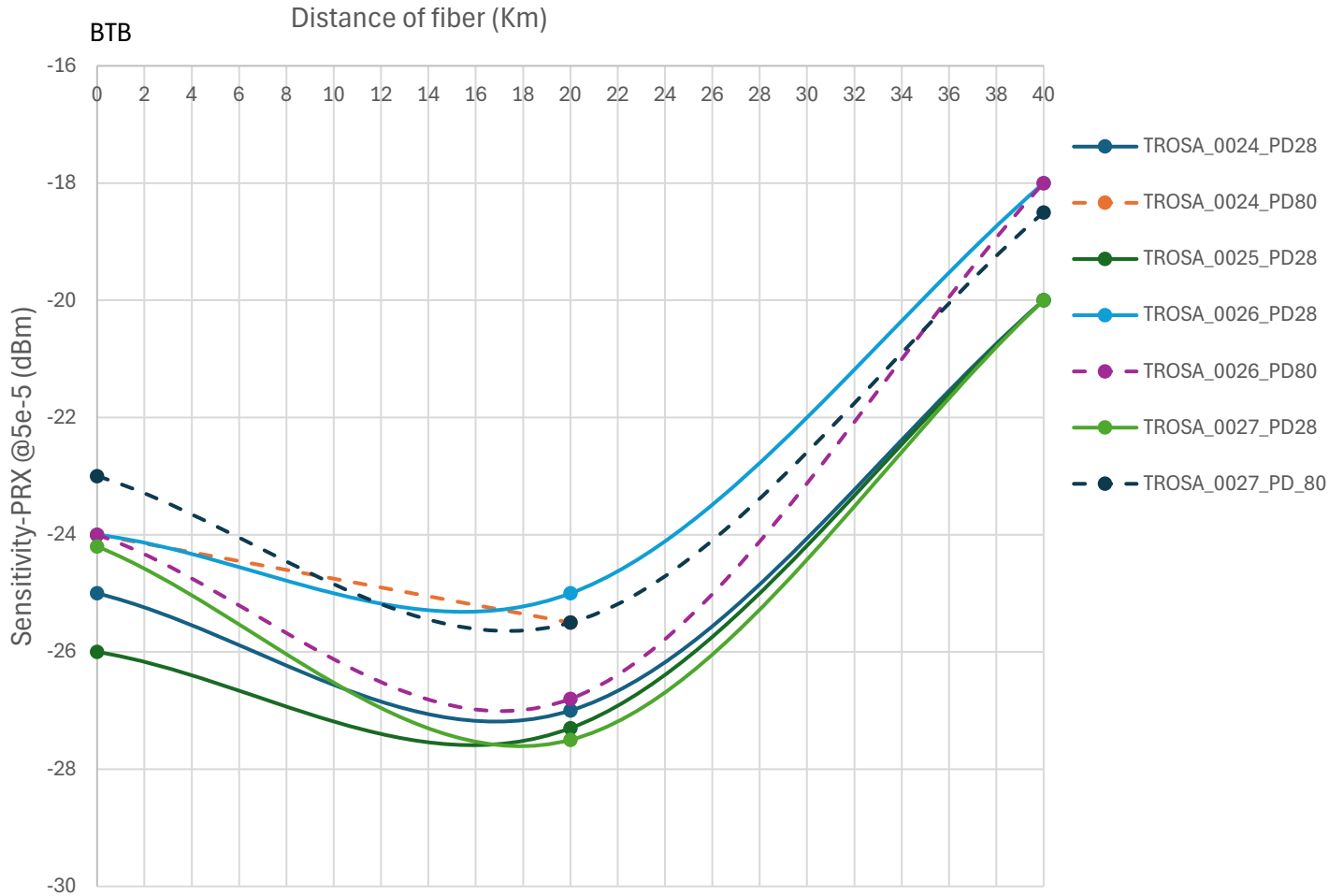
- The modulation signal is generated with Keysight N4951B pulse pattern generator (PPG). The modulation signal is a PRBS7/PRBS31 non-return-to-zero (NRZ) 25.78125 Gbps signal.
- The modulation signal modulates the ATOP transceiver, which is configured to wavelength 1550.92 nm
- The modulated optical signal is transmitted through 0, 20 or 40 km SSMF and variable optical attenuator (VOA) to adjust the received optical power (PRX), which is measured by a optical power meter (PM) using a 10% of the received signal.
- The optical signal is received with the BFC EV_TROSA , which contains the BFC QC PIC with balanced PD and BFC QC ASIC 072 with CDC, using PurePhotonic PPCL550 tunable laser as local oscillator (LO) with an optical power of 10 dBm.
- The BFC QC PIC splits the two polarizations of received signal with a polarization beam rotator and splitter (PBRs) and both polarization are rotated to TE polarization. Then, each of signal is joined with half of the LO in a 2x2 coupler. The signal and the LO are mixed using a balanced PD (BPD). Considering the LO wavelength is around 30 GHz away of the signal wavelength, the electrical mixed signal is an amplitude modulated signal over a 30 GHz electrical carrier and that will be denoted as intermediate frequency (IF) signal.
- The BFC QC ASIC amplifies the IF signal with a transimpedance amplifier (TIA). The IF signal still contains all the amplitude and phase information of the optical signal, so chromatic dispersion compensation (CDC) can be applied. This CDC circuit is an all-pass filter with a tailored group delay that compensates the chromatic dispersion for an specific distance. After the CDC, the IF signal is downconverted to a baseband signal using an envelope detector (ED). This analog signal processing has been done for both polarizations IF signals and after downconversion, they are added with an output buffer (OB).
- The electrical signal generated by the BFC EV_TROSA is time and amplitude recovered with a Semtech CDR GN2146 before the BER is counted by Keysight N4952A BER tester (BERT).

Summary of results

TROSAs	ASIC	Specs	PD	BW @-6dB (GHz)	Excess Insertion Loss (dB)				Sensitivity – BTB (dBm) [Best case]	Sensitivity – 20 Km (dBm) [Best case]	Sensitivity – 40 Km (dBm) [Best case]
					LO (EL1) Left	LO (EL2) Right	Signal (EL1) Left	Signal (EL2) Right			
TROSA_0024	072	Single wirebond	PD_28	28	0.13	0.11	1.55	1.9	-25	-27.5	-20
TROSA_0024	072	Single wirebond	PD_80	24	1.24	1.29	2.8	3.8	-24	-25.5	X
TROSA_0025	072	Single wirebond	PD_28	28	0.65	0.70	3.5	3	-26	-27.3	-20
TROSA_0025	072	Single wirebond	PD_80	No RF output	0.85	1.05	2.5	3.65	No RF output		
TROSA_0026	072	Double wirebond	PD_28	32	0.9	0.95	3	1.45	-24	-25	-18
TROSA_0026	072	Double wirebond	PD_80	30	0.85	1.05	2.51	3.65	-24	-26.8	-18
TROSA_0027	072	Double wirebond	PD_28	28	1.08	1.14	1.92	1.27	-24.2	-27	-20
TROSA_0027	072	Double wirebond	PD_80	26	1.25	1.45	3.2	4.4	-23	-25.5	-18.5

Sensitivity comparison

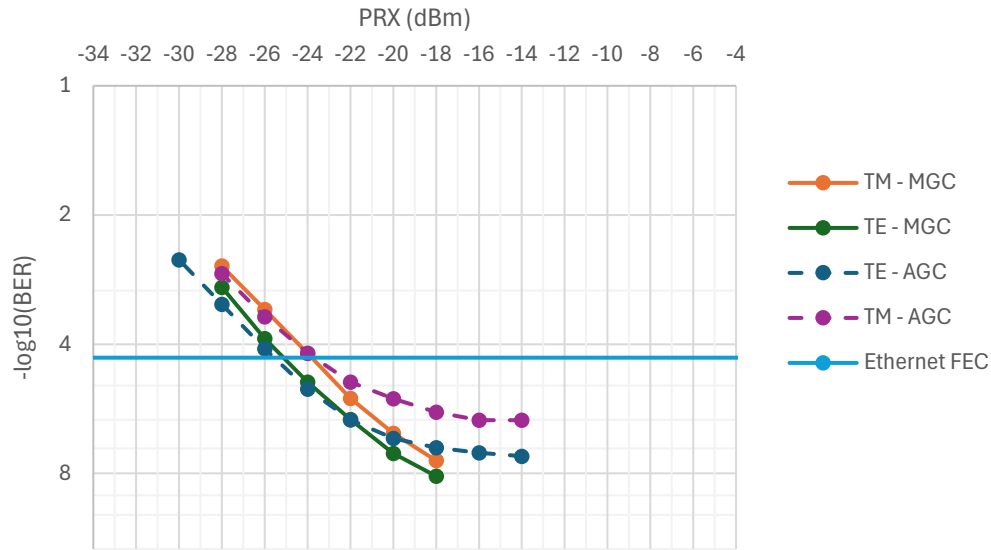
Graph of sensitivity vs Fiber distance (TE Polarization)



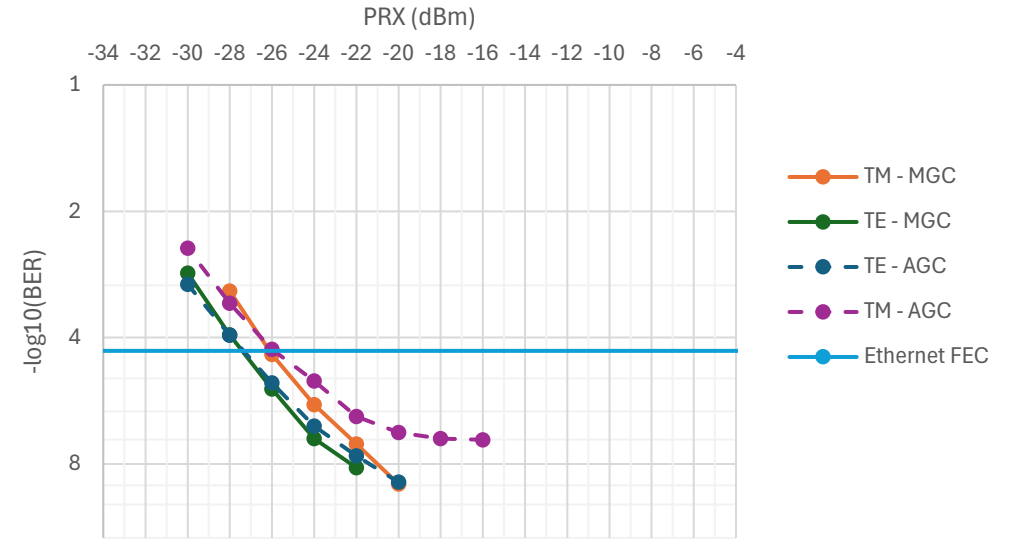
TROSA	Maximum Penalty due to Polarization
TROSA_0024_PD28	1.3 dB
TROSA_0024_PD80	1 dB
TROSA_0025_PD28	1 dB
TROSA_0026_PD28	1 dB
TROSA_0026_PD80	1.5 dB
TROSA_0027_PD28	0.5 dB
TROSA_0027_PD80	1 dB

MGC vs AGC comparison – TROSA_0024

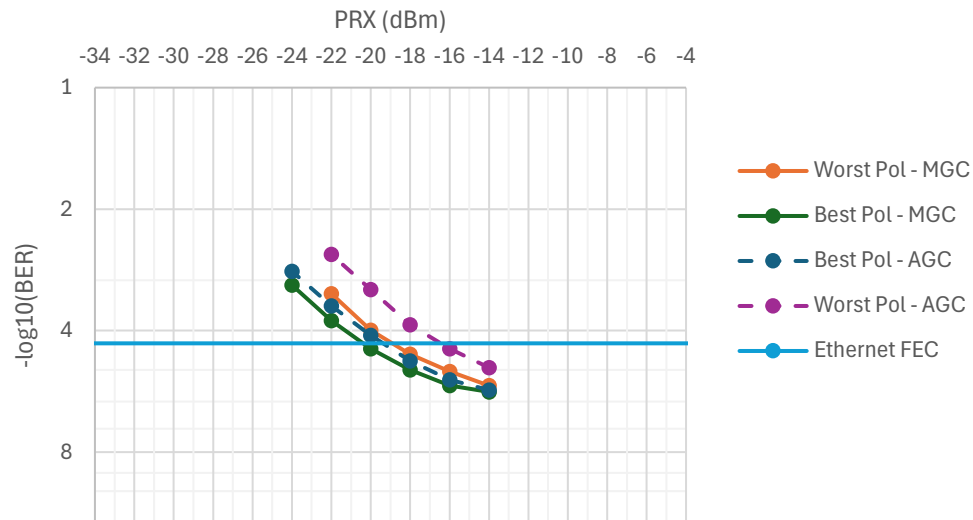
BTB_PD_28 (-34 GHz)-PRBS 31



20 Km_PD_28 (-26 GHz)-PRBS 31



40 Km_PD_28 (-32 GHz)-PRBS 31

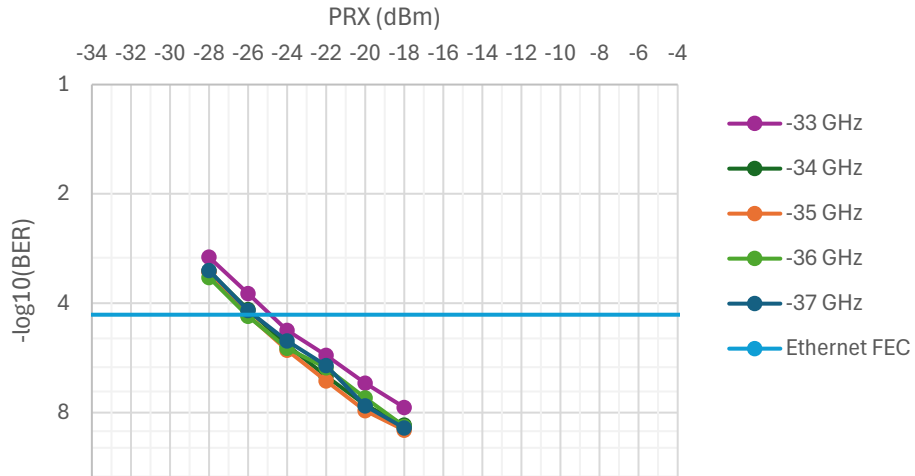


For 40 Km it was not possible to determine which arm is the signal aligned to, as the RSSI needed more power. Therefore, the best and the worst polarization was found out by observing the BER.

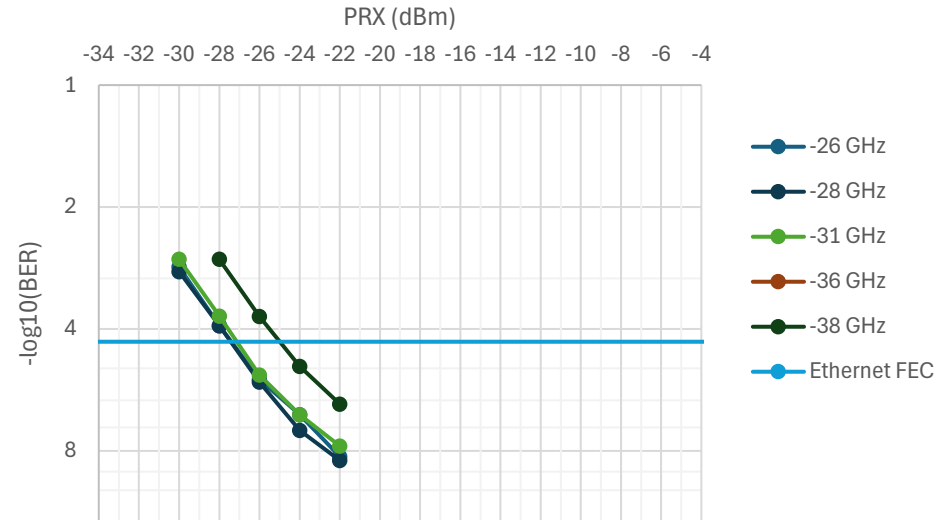
Fiber distance	Sensitivity – MGC (dBm)	Sensitivity – AGC (dBm)
BTB - TE	-25	-25.5
BTB - TM	-24	-24
20 Km - TE	-27.5	-27.5
20 Km - TM	-26	-26
40 Km – Best Pol	-20	-19.5
40 Km – Worst Pol	-19	-16.3

The range of working intermediate frequencies from 0 – 40 Km (TROSA0025 – MGC)

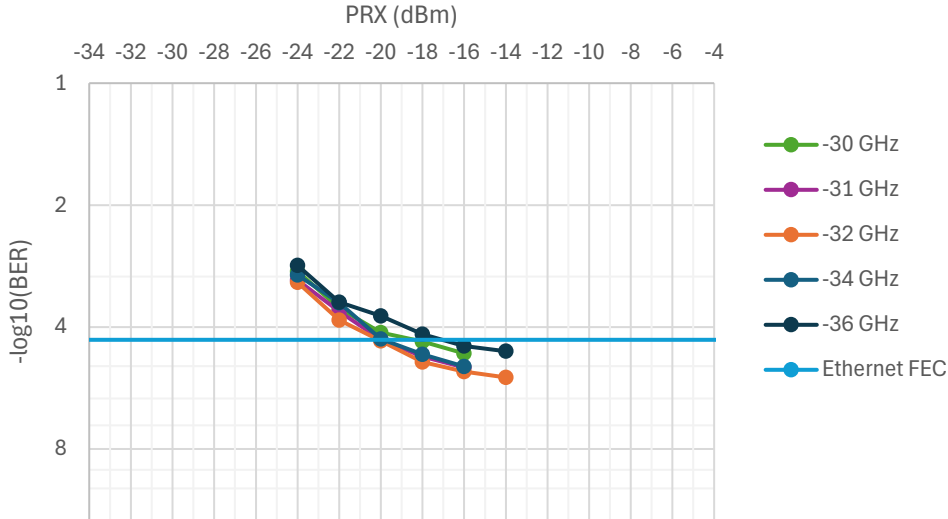
BTB_PD_28 -PRBS 31



20 Km_PD_28 -PRBS 31



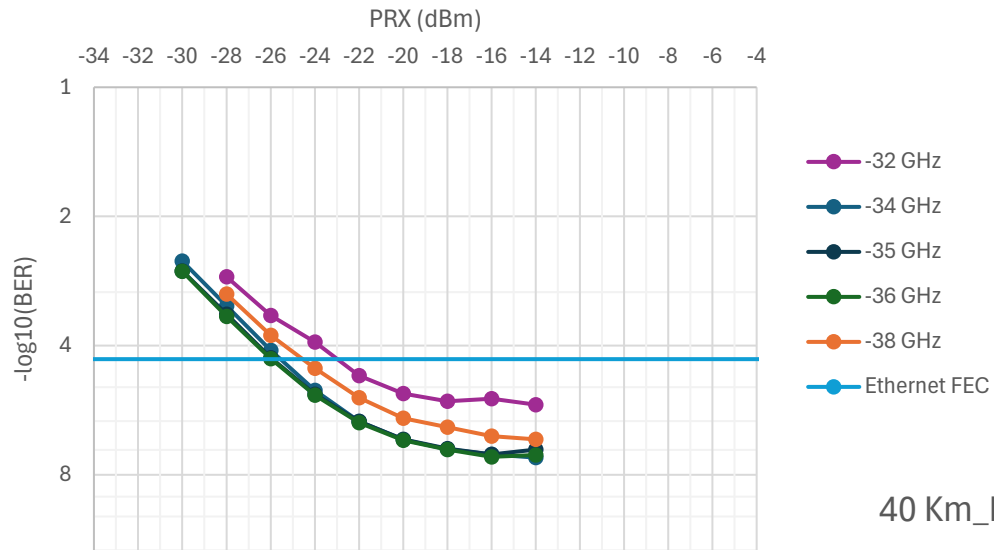
40 Km_PD_28 -PRBS 31



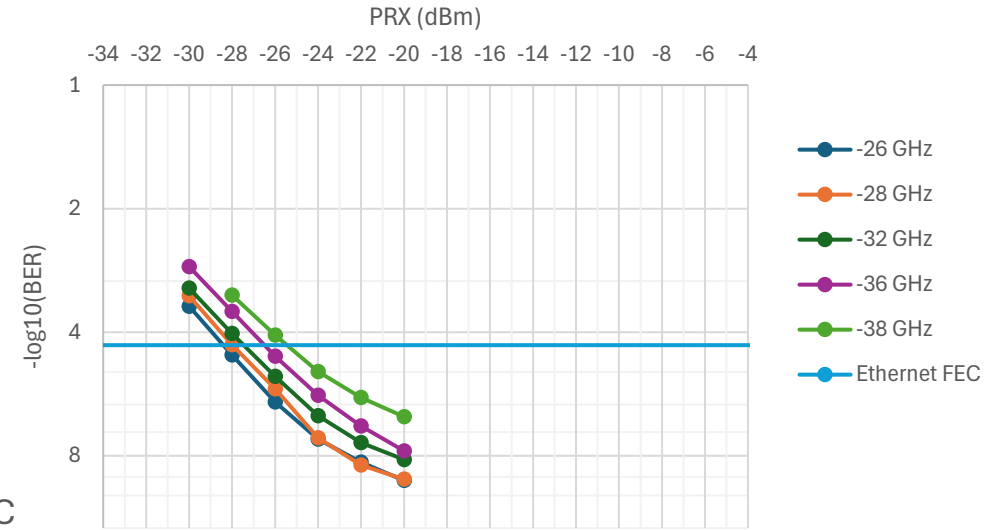
The ideal range of IF to have all the distances working under MGC operating condition is -33 GHz to -36 GHz.

The range of working intermediate frequencies from 0 – 40 Km (TROSA0024 – AGC)

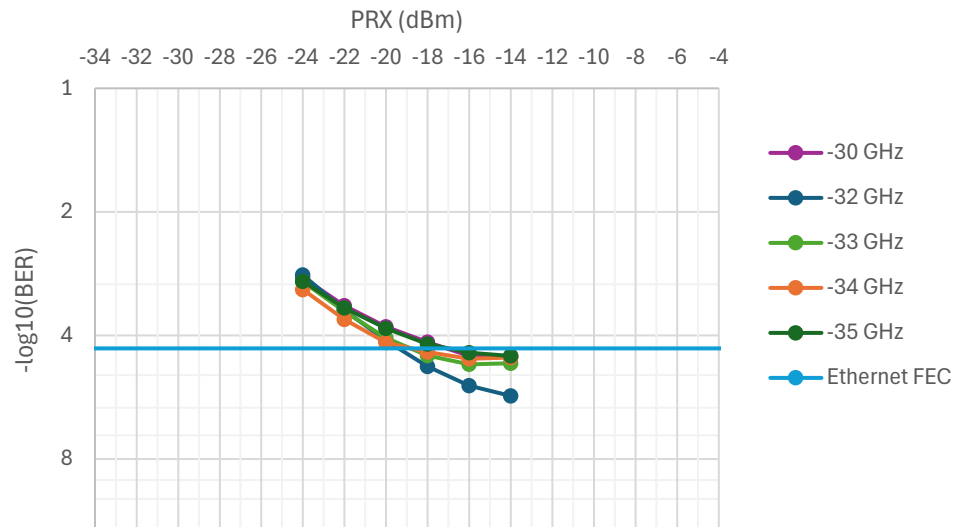
BTB_PD_28 -PRBS 31 - AGC



20 Km_PD_28 -PRBS 31 - AGC



40 Km_PD_28 -PRBS 31 - AGC



The ideal range of IF to have all the distances working under AGC operating condition is -32 GHz to -35 GHz.

Summary and Conclusion

- The best achieved sensitivity for different boards over distances of 0-40 Km for both the PDs (PD28 & PD80) were in the range of:
 - BTB: -23 dBm to -26 dBm
 - 20 Km: -25 dBm to -27.5 dBm
 - 40 Km: -18 dBm to -20 dBm

With the maximum penalty due to polarization being 0.5 dB to 1.5 dB.

- The boards with MGC had the best tolerance towards polarization, error floor and LO detuning.
- In general, PD28 outperformed PD80, so going forward PD28 will be used as PIC photodetector
- ASIC 072 in combination with the Silicon Photonics PIC have shown excellent performance from 0 to 40km with good performance for both AGC and MGC variants. This ASIC and PIC will be used in PIC ROSAs and SFP transceivers
- These results are record breaking and highly attractive for both Fronthaul and upgrades of DWDM networks for both Cable and Telecom Operators

Appendix 5 - Bulk ROSA Test Report 1

Alpha Prototype Test Report

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Abstract

A set of multiple measurements were performed on the alpha-prototypes of Bifrost communications' 25 Gbps Quasi-coherent receiver optical sub assembly (QC-ROSA) for mobile fronthaul to characterize its performance. Two different sets of QC-ROSAs were manufactured: 2 by AVO, where only 1 was working due to an electrical short inside the module, and 15 by the Youopto. Due to challenges in sourcing the housing, only two QC-ROSAs were received from AVO instead of the originally planned three.

For the AVO QC-ROSA, excess insertion loss in the signal path is 1.1 dB and 1.2 dB for the two polarization arms. This is better than the requirement specification of 1.5 dB.

For the Youopto QC-ROSAs, average excess insertion loss in the signal path is 1.6 dB and 1.9 dB for the two polarizations, and thus slightly higher than the requirement specifications.

For the LO arm, excess insertion loss is better than requirement specs for all QC-ROSAs from both suppliers.

The good optical coupling in the LO path compensates the excess loss in the signal arm. Therefore, the Combined signal and LO insertion loss is within requirement specifications for the 1 AVO build and for 14 out of 15 Youopto builds.

The input 6-dB bandwidth of all ROSAs is 26 GHz and is within requirement specifications.

Due to the advancements in ASIC design during the project duration, an ASIC with improved CDC and SSB filters were used, resulting in an increase in reach to 30 km for all ROSAs. This is 50% better than requirement specifications

Receiver sensitivity for the AVO QC-ROSA is -21 dBm B2B and -18 dBm after 30 km SSMF transmission for the polarization with the best performance. Polarization dependency is approximately 3 dB B2B rising to approximately 6 dB after 30 km SSMF transmission.

For the Youopto QC-ROSAs, the average B2B receiver sensitivity is -18 dBm and -13 dBm after 30 km SSMF transmission. The spread over the 15 QC-ROSAs from Youopto is quite large with approximately 7 dB difference between the best and worst performing unit. This highlights the difficulty in aligning LO and Signal beams perfectly at the PD surface, and thereby the challenge in achieving a high yield in production of the bulk optics QC-ROSA.

Apart from higher polarization dependence, the AVO QC-ROSAs show similar performance to the best Youopto QC-ROSA. The increased polarization dependence in the AVO QC-ROSAs is caused by back-reflected signal light entering the LO laser. In future builds, an optical isolator will be placed in front of the LO laser. The Youopto QC-ROSAs have the isolator included.

Introduction

This report summarizes the measurement characterization of the alpha prototypes of the QC-ROSA. Two versions have been tested using AVO in the USA and Youopto in China respectively for the assembly. For the AVO version, a single working unit was received due to difficulties in sourcing functioning housings. Therefore, there is no statistical analysis of the performance of the AVO build. For the Youopto builds, 15 units were received. This report contains statistical analysis of their performance. All tests have been performed on QC-ROSAs constructed with an improved version of the ASIC designed for the 25 Gbps fronthaul case. Since the only difference in design between the 3 use-cases (10 Gbps NG-PON2, 25 Gbps Fronthaul, and 25 Gbps long-reach) lies in the ASIC design, all conclusions on the QC-ROSA implementations highlighted in this report are valid for the 2 other use-cases as well. Due to the supply-chain challenges for the housing, it was decided to focus on the commercially strongest of the 3 use cases, and achieve valuable statistical information from having a large quantity of identical samples rather than splitting the batch between different ASICs.

For the AVO build, 2 units were received of which one is working and one not working due to an internal electrical short. The housing from these two were supplied by Streamtech and were the only two useable ones out of a large batch of housings. The remaining housings had undergone severe mechanical deformations during the curing of the ceramic assembly, thus making them useless for precision mounting of optical components. AVO has engaged two alternative housing suppliers (Kyocera, Japan and First Optoelectronics, China), but those housings have not arrived yet. The performance of the working AVO QC-ROSAs showed a clear improvement over the designs from Youopto, thus proving the improved optical design in the alpha-prototypes from AVO. A high polarization dependence was observed and analysed, leading to the conclusion that the polarization dependence originated from the lack of an optical isolator in front of the LO laser to protect it from back-reflected signal light. Optical isolators have been procured and will be used in future QC-ROSAs from AVO.

The changes in lens design leading to the improvement in the AVO QC-ROSAs over the Youopto ROSAs were transferred to Youopto (which includes an optical isolator in the LO path), and a batch of 15 ROSAs were ordered from them. This report summarizes the measurements and characterization of the 1 working AVO alpha-prototype and the 15 Youopto prototypes.

Figure 1 shows the picture of one of the ROSA produced by AVO mounted on an evaluation PCB in a test jig suitable for lab testing. The Youopto builds were mounted in similar fashion.

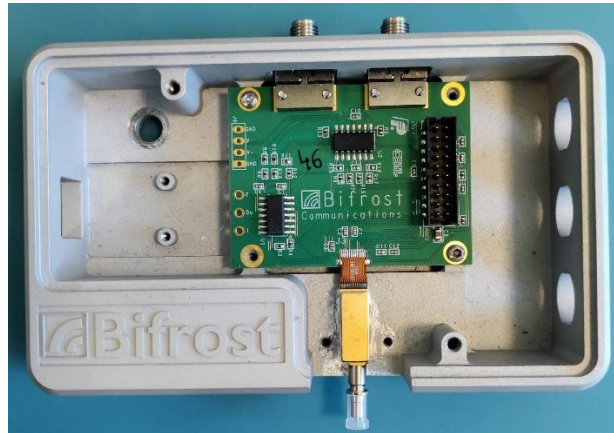


Figure.7.Picture.of.ROSA.from.the.second.supplier.(QCR7A660)

For characterizing and qualifying the performance of the ROSAs the following set of measurements were done:

- **Measurement of Excess Losses:** To determine the excess losses higher than the theoretical insertion losses
- **Performing the Frequency sweep:** To determine the frequency spectrum of the ROSA
- **Measurement of Receiver Sensitivity over different distances of standard single mode fiber (SSMF):** To determine the minimum optical power required to achieve a specified error rate limit. In this case, the Ethernet FEC limit ($5e-5$)

The report starts by outlining a block diagram of the two different setups used for the measurements mentioned earlier, detailing the different system components and describing the overall operation of each setup. It then presents the measurement results for the QC-ROSA from AVO, noting that the addition of an optical isolator was necessary but could not be implemented on time due to the before mentioned challenges in sourcing the housing.

For the prototypes assembled by Youopto, the results of the best performing unit are present along with statistical data based on measurements of all 15 prototypes.

1. Experimental Setups

To perform the measurements on the QC-ROSAs, two different setups have been used. This section presents the two different setups and explains its functions and importance towards the measurement of the ROSAs.

1.1 Setup for measuring input bandwidth

The setup shown in Figure 2 is used for performing a frequency sweep on the QC-ROSA. The frequency sweep measurement allows to characterize the input bandwidth (BW) of the ROSA, i.e. the combined BW of the photodiode (PD), the transimpedance amplifier (TIA) and the different filters (including the chromatic dispersion compensation filter (CDC) filter). The setup consists of an external modulated laser (EML) transmitter driven by low frequency signal generated by a pulse pattern generator (PPG). The modulated signal is then transmitted through a standard single mode fiber (SSMF), which is then connected to a variable optical attenuator (VOA) and a power meter (PM). The attenuated signal is then transmitted through a polarization controller before it reaches the quasi-coherent ROSA (QC-ROSA). Simultaneously the local oscillator (LO) present inside the ROSA is activated at a specific wavelength such that it matches with the signal wavelength. One end of output of the ROSA is connected by a load capacitor and the other end is connected to a digital communications analyser (DCA) which acquires the eye diagram of the processed signal. The whole system is controlled by a program externally which then sweeps over a range of intermediate frequencies (IF) at a specific power to acquire the frequency spectrum of the ROSA.

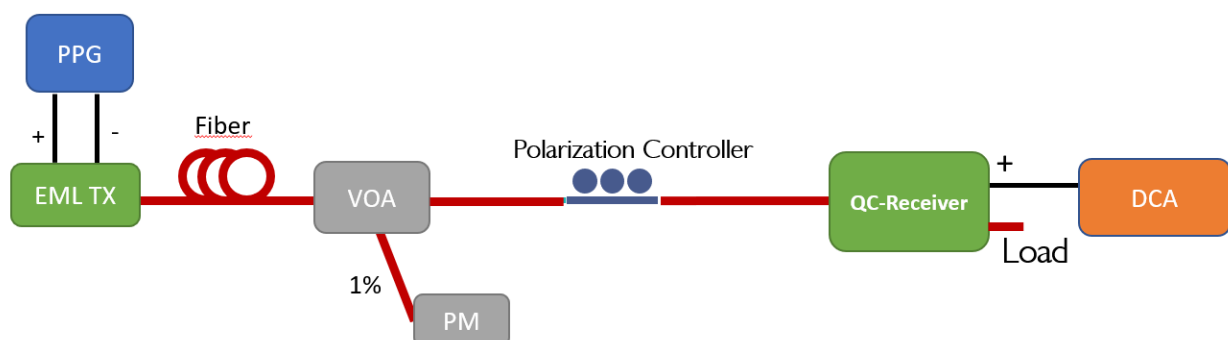


Figure.8 Setup for Performing the frequency sweep

As indicated before this setup is important as it acquires the frequency spectrum and presents the operational bandwidth of the ROSA. The flatter and broader the frequency response the higher the bandwidth available for operation for the ROSA.

1.2 Setup for measuring the sensitivity

For measuring the sensitivity of the QC-ROSA, the setup shown in Figure 3 is used. This setup is similar to the one used for the frequency sweep until the signal reaches the QC-ROSA. Here, the two outputs of the QC-ROSA are connected to a commercial clock data recovery circuit (CDR) which is used for clock recovery and signal equalization. The processed signal from the CDR is then transmitted to a bit error rate (BER) test setup which calculates the error between the transmitted and the received bits.

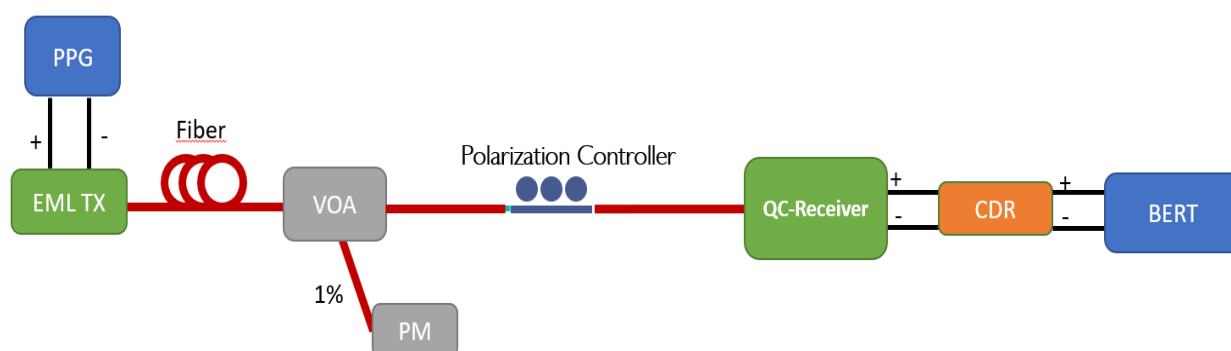


Figure.9.Setup.for.measuring.the.sensitivity

After acquiring the frequency spectrum of the ROSA, a set of measurements are done to identify the optimum intermediate frequency (IF) for each fiber transmission distance. Once the optimum IF is identified, the bit error ratio (BER) is measured while varying the receiver input power levels for 3 different cases of polarization. This is done at the optimum IF between signal and LO laser for a specific distance of fiber, which then paves the way to plot the sensitivity curve for the ROSA under different fiber distances. The different polarization cases are: 100/0- the polarization completely is aligned to the non-inverting arm (left arm) of the ROSA, 0/100- the polarization is completely aligned to the inverting arm (right arm), 50/50- the polarization is divided between the two arms. Ideally, there should be no polarization dependence. A polarization dependence of up to 1.5dB can be accepted in most use-cases.

2. Measurements on the QC-ROSA from AVO

This section presents the results from the measurements done on the ROSA from the first supplier and discusses the considerations made from the results obtained.

2.1 Insertion Loss

Insertion loss is a measure of power loss between the input and output of any given path or a system. The theoretical insertion losses for the ROSA are 7 dB for LO to the photodetector (PD) (3 dB from the polarizing beam splitter (PBS) and 4 dB from the asymmetric coupler), and 5.2 dB from the input receptacle to the PD (3 dB from the PBS and 2.2 dB from the asymmetrical coupler). For the 0/100 and 100/0 there are no theoretical losses associated with the PBS in the signal path. Any extra losses that are presented higher than the theoretical insertion loss is referred to as excess loss. Requirement specifications for the QC-ROSAs are less than 1.5 dB excess insertion loss for both signal and LO.

For measuring the excess losses, the received signal strength indicator (RSSI) values are noted down when the signal and LO are turned on separately and the insertion losses for LO to PDs and signal to PDs are calculated. Finally, the excess losses are calculated by subtracting the measured insertion losses from the theoretical insertion loss. The excess losses measured for the ROSA from AVO are shown in Table 1.

Table 1: Excess Loss results for the ROSA from the first supplier

Excess Loss (dB)			
LO to left PD (EL _{LO1})	LO to Right PD (EL _{LO2})	Signal to left PD (EL _{S1})	Signal to right PD (EL _{S2})
0.569	0.392	1.0557	1.2405

Excess loss for the LO path is less than 0.6 dB in both the arms and excess loss for the signal path is less than 1.5 dB in both the arms. These values are well within the requirement specifications.

2.2 Input Frequency response

The frequency response of the ROSA is shown in Figure 4, this measurement was carried by using the setup as shown in Figure 2. The transmitter used here is a commercially available ATOP transceiver with an operating wavelength of 1550.92 nm and this was driven by a Keysight pulse pater generator (PPG) at a data rate of 3 Gbps with a non-return-to-zero (NRZ) signal. By sweeping the LO laser wavelength while keeping the signal wavelength constant, and monitoring the output amplitude of the electrical output signal from the QC-ROSA, the input frequency response of the combined PD-wirebond-ASIC can be measured.

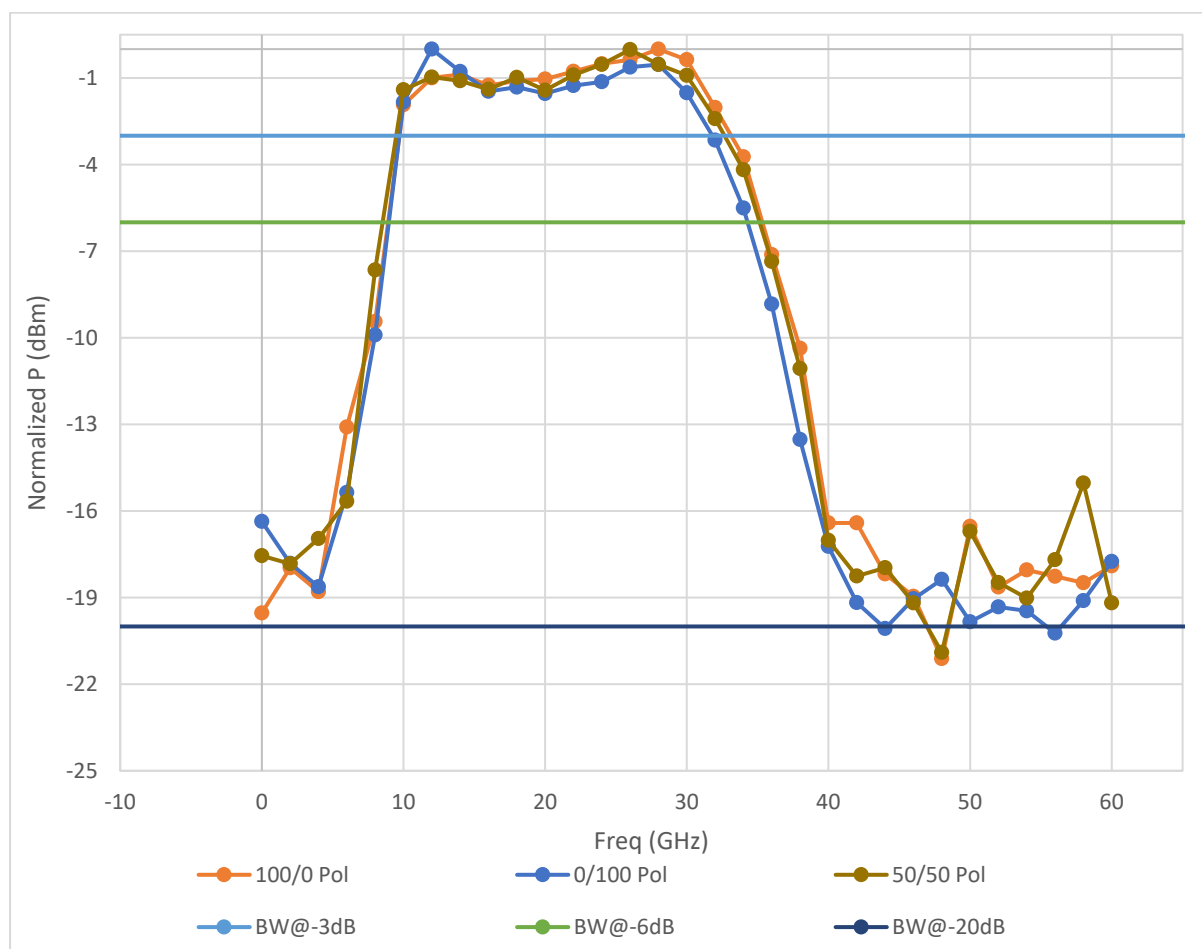


Figure.0.Frequency.Sweep.for.the.ROSA.from.the.first.supplier_Signal.power±.88.dBm?gain±.9;62V

From the frequency sweep results it is observed that the ROSA has a relatively flat response with a 6-dB bandwidth of 26 GHz. The measurement was performed with a LO power (P_{LO}) of 9 dBm, a LO wavelength (λ_{LO}) of 1552.47 nm and with a gain of 3.06 V. This is within the requirement specifications of the QC-ROSA

2.3 Sensitivity measurements

The results for sensitivity measurements done on the ROSA is shown in the form of a sensitivity curve in Figure 5. The measurements were done with the setup described in Figure 3 and were done for optical back-to-back (BTB), i.e. with 0 km of standard single-mode fiber (SSMF) and for other transmission distances 10km, 20 Km and 30 Km, initially for three different cases of polarization as mentioned in Section 1.

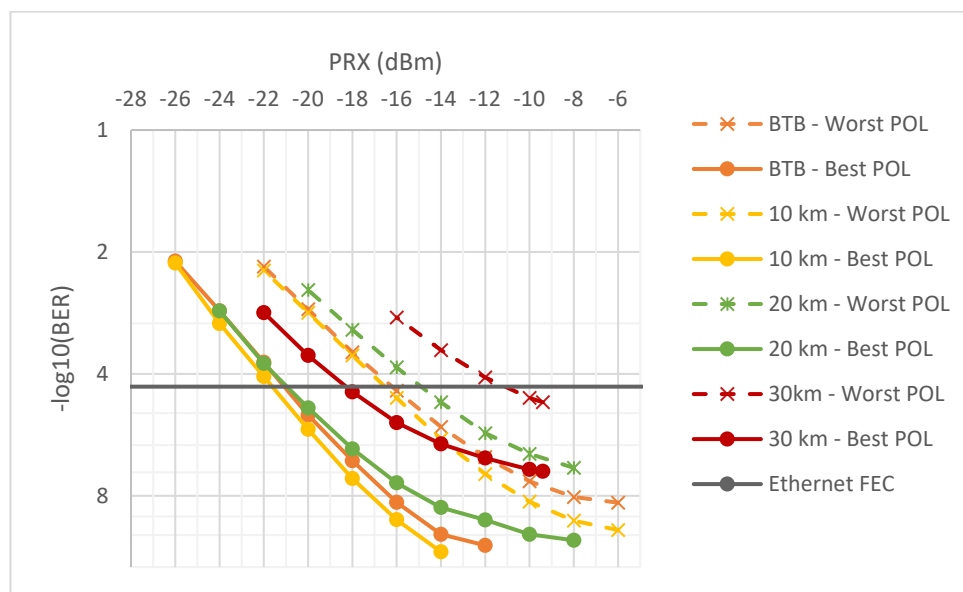


Figure 5: Sensitivity curves for the ROSA from the first supplier for BTB and different transmission distances

The results for the sensitivity measurements are presented in Table 2. Initially the measurements were done only for the three different polarization cases, however a significant variation in sensitivity was observed due to polarization. Therefore, two more measurements were done to find the polarization case with the best sensitivity and the worst sensitivity and plotting the sensitivity curve for the same. The optimum IF for BTB was -32 GHz and the optimum IF for transmission distances – 10 Km, 20 Km and 30 Km was -31 GHz

Table 2: Results of BTB sensitivity measurements for the ROSA from the first supplier

Sensitivity	PRX @ 5e-5
BTB-Best Pol	-21 dBm
BTB-Worst Pol	-16.1 dBm
10 Km-Best Pol	-21.7 dBm
10 Km-Worst Pol	-16.5 dBm
20 Km-Best Pol	-21 dBm
20 Km-Worst Pol	-15 dBm
30 Km-Best Pol	-18.1 dBm
30 Km-Worst Pol	-11 dBm

The measured receiver sensitivity for the best polarization case exceeds the target in the project for all transmission distances. The up to 7 dB polarization dependence (30 km), however, is too high for network operators to accept even if the worst-case polarization would have sufficient performance. This large polarization dependence may trigger unwanted reactions from network management systems, and must therefore be reduced to below 1.5 dB. To investigate more on the polarization dependence, a set of measurements were done to test polarization stability of the ROSA. The details about polarization stability test and the results for the same are elaborated in section 2.3.1.

2.3.1 Polarization stability measurements

The results from the polarization stability measurements are shown in Figure 6. These measurements were carried out by varying the polarization randomly for around 30 iterations and measuring the BER for each of the iteration, this presents a statistical analysis of the polarization stability over different polarization.

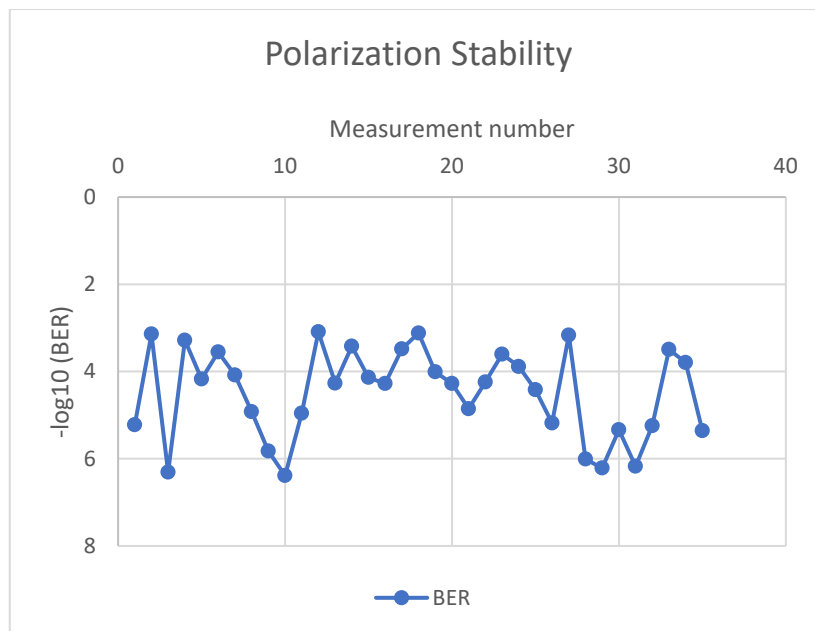


Figure 6. Polarization stability measurements for the ROSA from the first supplier

From the above figure the polarization is very unstable over different iterations of the polarization controller. After some investigation and discussion with supplier it was concluded that, the reason for the polarization dependence might be due to the absence of an isolator in the LO path, which leads to back reflections interfering with the LO laser causing it to generate

excess noise, which degrades system performance for certain polarizations. To solve this, an optical isolator will be inserted in the LO optical path in the next builds by AVO.

Apart from the polarization dependence, the AVO prototype meet requirement specifications on all criteria, and increase transmission distance from 20 km to 30 due to the advancements made in Bifrost ASIC design during the project.

3. Measurements on Youopto ROSAs

This section presents the results of measurements made on the ROSAs from Youopto. A total of 15 ROSAs were measured in this batch. As mentioned in section 2.3.1 these ROSAs have a different optics scheme than the ROSA from Avo and have an isolator present in the path of the LO.

3.1 Complete results of the best-case QC-ROSA (QCR1A0027)

Out of all the 15 ROSAs measured, the QC-ROSA with the best receiver sensitivity is chosen and the complete results of the measurements made on it are presented in this section. In the next section a statistical analysis of results from all the 15 QC-ROSAs are presented. The procedure for measurements is identical to the ones incorporated for the QC-ROSA from AVO.

3.1.1 Insertion Loss

As mentioned in section 2.1 the theoretical insertion losses for LO to PDs are 7dB and for the signal to PDs are 2.2 dB for the 0/100 and 100/0 cases where the signal polarization is aligned to a single arm in the QC-ROSA. Any extra losses higher than the insertion loss are the excess losses. The excess loss for ROSA-QCR10027 is presented in Table 3. The procedure for measuring the excess loss is the same as the one mentioned in section 2.1.

Table 3: Excess loss results for the ROSA-QCR1A0027

Excess Loss (dB)			
LO to left PD (EL_{LO1})	LO to Right PD (EL_{LO2})	Signal to left PD (EL_{S1})	Signal to right PD (EL_{S2})
0.2865	0.0721	0.9367	0.9367

Excess loss for the LO path is less than 0.3 dB in both the arms and for the signal path it is less than 1 dB in both the arms. These are below the requirement specifications for the QC-ROSA.

3.1.2 Frequency Response

The frequency sweep measurement for QCR1A0027 was carried out by using the setup as shown in Figure 2 from section 1. The specifications of the instruments and the parameter settings are the same as the one mentioned in section 2.3.

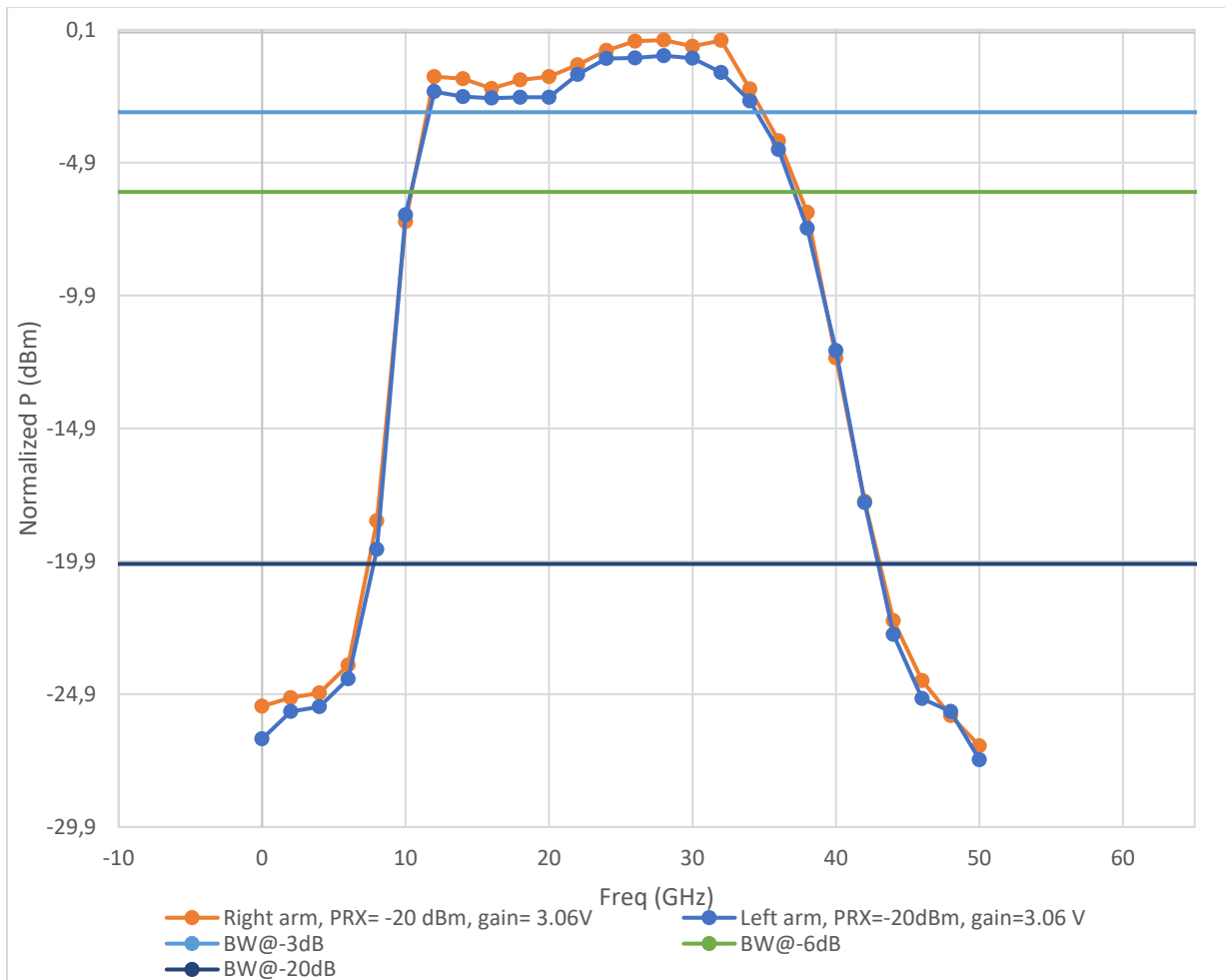


Figure 3 Frequency sweep for the ROSA_QCR7A668@_Signal.power.±.86.dBm?gain±.9;6@V

The measurement was performed with a P_{LO} of 9 dBm, λ_{LO} of 1550.63 nm and with a gain of 3.06 V. From the frequency sweep it can be seen the ROSA has a 6-dB bandwidth of 26 GHz, identical to the AVO QC-ROSA. This is within the requirement specifications for the QC-ROSA.

3.1.3 Sensitivity Measurements

This section presents the sensitivity results for QCR1A0027 for fiber distances of BTB, 10 Km, 20 Km and 30 Km. The sensitivity measurements were done using the setup as described in figure 3 from section 1.

BTB

The sensitivity measurements done on QCR1A0027 with BTB are presented in form of a sensitivity curve in figure 8. The measurements were done for three different polarization cases as mentioned in section 1.

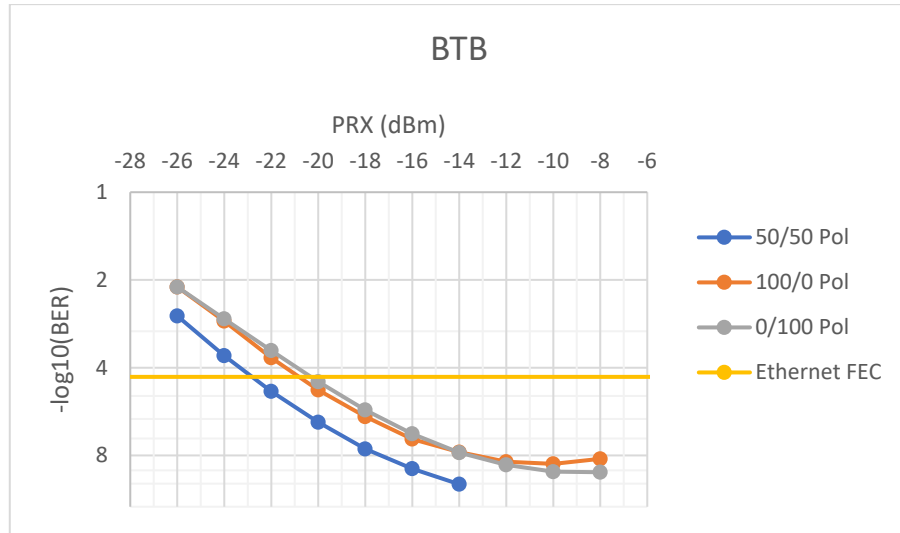


Figure 4. Sensitivity Curve for QCR7A668 for BTB with IF ± 98 GHz

The results for the sensitivity measurements for QCR1A0027 with BTB are shown in Table in 4. It presents the values for sensitivity for three different polarizations.

Table 4: Results of sensitivity measurements for QCR1A0027 for BTB

Sensitivity	PRX @ 5e-5
0/100 Pol	-20.5 dBm
50/50 Pol	-23 dBm
100/0 Pol	-21 dBm

10 Km

The sensitivity measurements for QCR1A0027 with a 10 Km SSMF are presented in form of a sensitivity curve in figure 9.

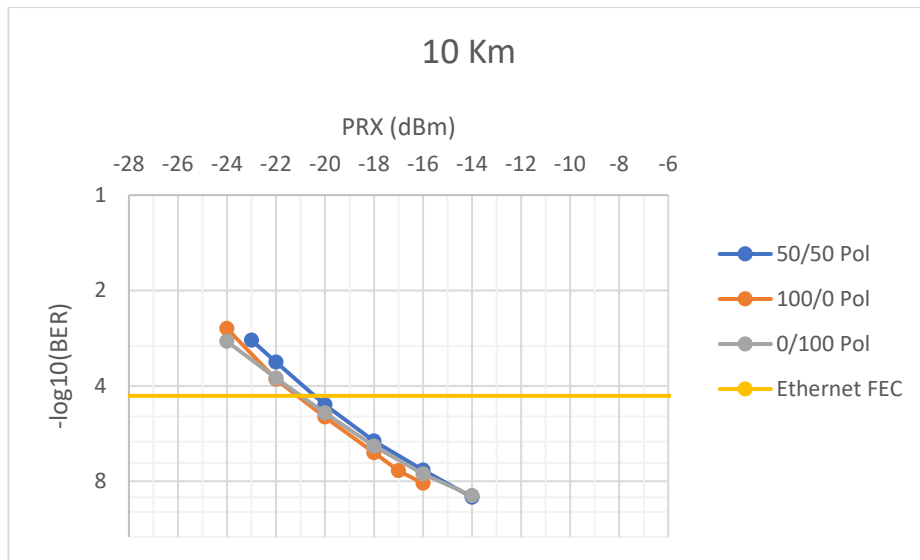


Figure 6: Sensitivity Curve for QCR7A668 for 10 Km with IF ± 96 GHz

The results for the sensitivity measurements with 10 Km are shown in table 5. Like the case of BTB it also presents the sensitivity values for three different polarization cases. The difference between the worst and the best sensitivity is very minimal around 0.5 dBm.

Table 5: Results of sensitivity measurements for QCR1A0027 for 10 Km

Sensitivity	PRX @ 5e-5
0/100 Pol	-21 dBm
50/50 Pol	-20.5 dBm
100/0 Pol	-21 dBm

20 Km

The sensitivity measurements for QCR1A0027 with a 20 Km SSMF are presented in form of a sensitivity curve in figure 10.

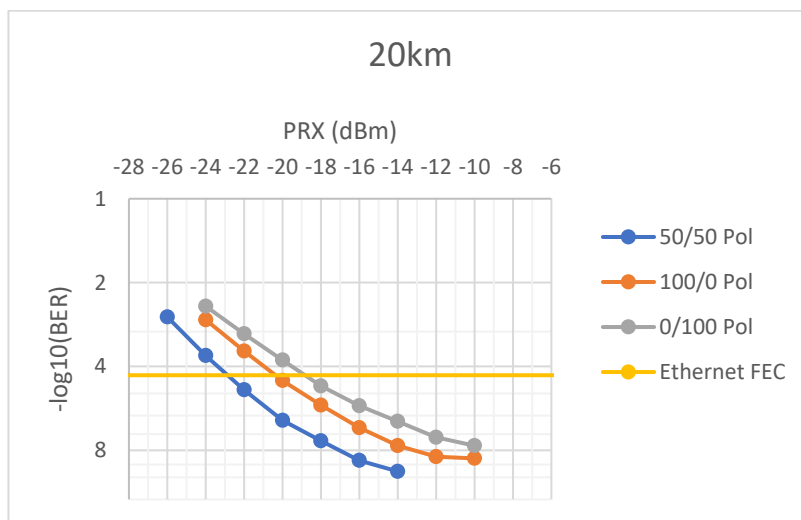


Figure.76.Sensitivity.Curve.for.QCR7A668for.86.Km.with.IF.±.8GHz

The results for the sensitivity measurements with 20 Km are shown in table 6. Like the previous cases with BTB and 10 Km it also presents the sensitivity values for three different polarization cases. There is a difference of 3.8 dBm between the worst and the best sensitivity measured due to the variation caused by polarization.

Table 6: Results of sensitivity measurements for QCR1A0027 for 20 Km

Sensitivity	PRX @ 5e-5
0/100 Pol	-19 dBm
50/50 Pol	-22.8 dBm
100/0 Pol	-20 dBm

30 Km

The sensitivity measurements for QCR1A0027 with a 30 Km SSMF are presented in form of a sensitivity curve in figure 11.

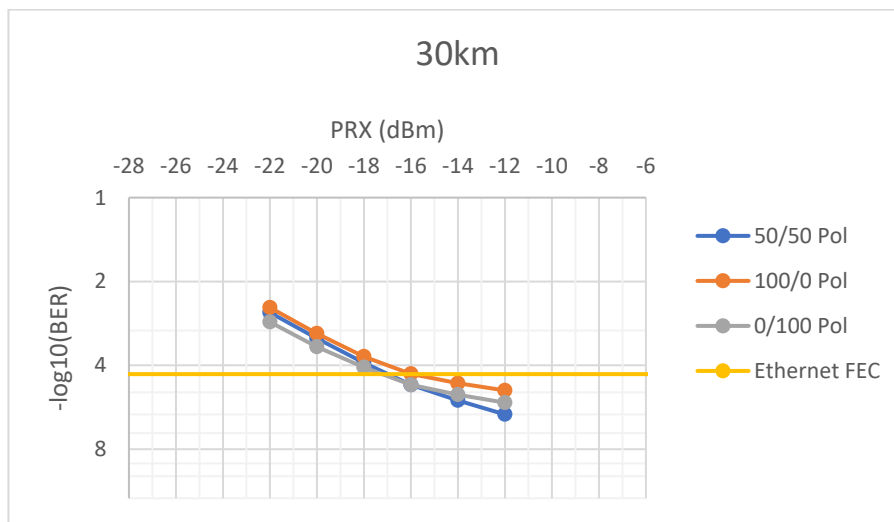


Figure.77.Sensitivity.Curve.for.QCR7A668for.96.Km.with.IF.±.8GHz

The results for the sensitivity measurements with 30 Km are shown in table 7. Like the previous cases with other fiber distances, it also presents the sensitivity values for three different polarization cases. The difference between the worst and the best sensitivity measured caused by the changed in polarization is around 1 dBm.

Table 7: Results of sensitivity measurements for QCR1A0027 for 30 Km

Sensitivity	PRX @ 5e-5
0/100 Pol	-17 dBm
50/50 Pol	-17 dBm
100/0 Pol	-16 dBm

Overall, the receiver sensitivity for this Youopto QC-ROSA is better than the requirement specifications, but the polarization dependence of up to 3.8 dB is too high. Since the LO cannot be affected by back-reflections due to the optical isolator, we attribute this to difference in signal/LO waveform overlap at the two PDs. This highlights the challenges in the bulk optics QC-ROSA implementation and supports the use of a photonics integrated circuit (PIC) implementation where perfect overlap is secured by waveguidance.

3.2 Statistical analysis of all Youopto QC-ROSAs

The previous section presented the results of the ROSA with receiver sensitivity from the 15 QC-ROSAs. This section presents a statistical analysis of results from the measurements made on the 15 QC-QC- ROSAs.

3.2.1 Summary of Insertion Loss for the 15 QC-ROSAs

This section presents the results from the excess losses measurements made on the 15 QC-ROSAs. As mentioned in section 2.1, the excess losses are any extra losses higher than the theoretical insertion loss. The results for the excess losses are presented in table 8.

Table 8: Summary of excess losses for the 15 ROSAs

ROSA	Excess Loss (dB)			
	LO to left PD (ELO _{LO1})	LO to Right PD (EL _{LO2})	Signal to left PD (EL _{S1})	Signal to right PD (EL _{S2})
QCR1A0027	0.2865	0.0721	0.9367	0.9367
QCR1A0028	1.11948	0.45658	1.84749	2.07026
QCR1A0029	1.09203	0.81802	2.38625	2.30507
QCR1A0030	1.21228	0.51211	1.6356	1.56721
QCR1A0031	1.27845	1.4932	1.36826	1.70509
QCR1A0032	3.16987	1.19357	4.71539	0.99578
QCR1A0036	1.12867	0.38621	2.63931	2.46897
QCR1A0038	2.8575	1.14712	2.72705	2.22538
QCR1A0039	1.073816	0.552207	0.995779	2.30507
QCR1A0041	0.95728	0.71642	2.38625	2.07026
QCR1A0042	1.82583	1.20291	1.6536	1.17803
QCR1A0043	1.326329	0.456579	0.544157	0.598107
QCR1A0044	0.64999	0.53612	2.22538	1.70509
QCR1A0046	0.87839	0.62534	1.17803	0.82087
QCR1A0047	1.33597	0.115632	0.995779	1.240516

Average	1.346159	0.685608	1.882335	1.612827
Std Deviation	0.733856	0.398246	1.002328	0.595909

From table 8 it can be seen that the average excess loss for both LO to PDs and signal to PDs are all less than 2 dB for the signal and less than 1 dB for the LO. The total excess insertion loss is within requirement specification if it is taken into account the better than specified LO coupling compensates for the excess signal loss. In general, the path of LO to PDs have comparatively less losses than the path of signal to PDs. This is the case for all units with the exception of QCR1A0032, which appear to have a poorly aligned left PD.

We conclude that the insertion loss is within the requirement specification for 14 out of 15 units, which can be considered an excellent result.

3.2.2 Statistical analysis of sensitivity results for the 15 ROSAs

This section presents a statistical analysis of sensitivity results for the 15 ROSAs. For this a summarized plot of sensitivity vs distance of fiber distance over the 15 ROSAs. The plot as shown in figure 12 has three different datasets. The first dataset has the worst sensitivity achieved for a specific distance of fiber over the 15 ROSAs, the second one has the average value sensitivity for a specific distance over the 15 ROSAs and finally the third one has the best sensitivity achieved for a specific distance of fiber over the 15 ROSAs.

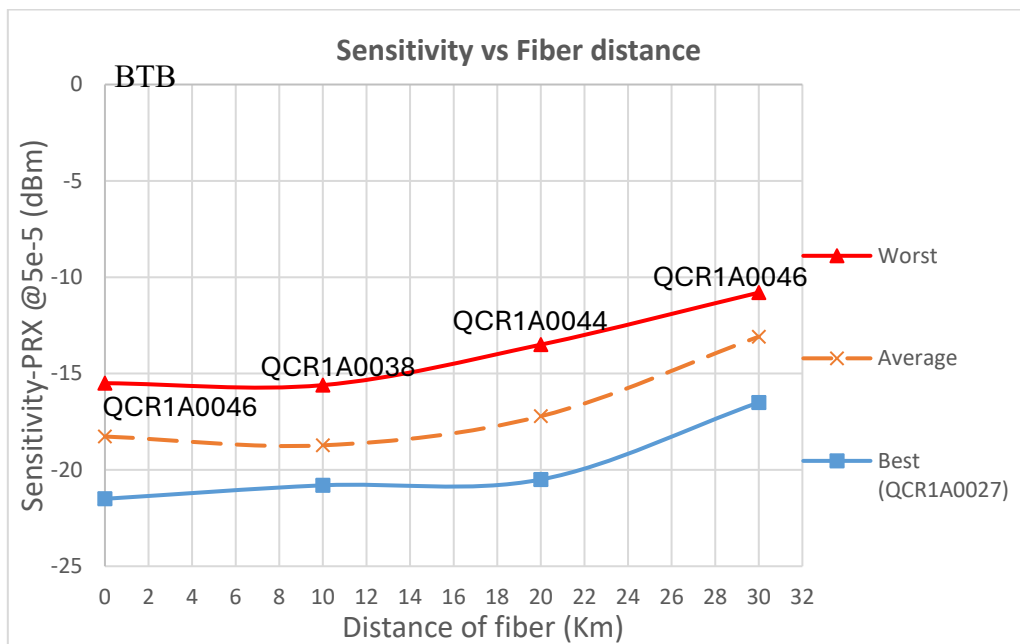


Figure.78.Statistical.results.of.sensitivity.for.the.ROSAs.from.the.second.supplier

In figure 11 for the worst sensitivity dataset, each point has been marked with a specific ROSA's name. This means that for that specific distance of fiber, the worst sensitivity achieved was by that specific ROSA when compared to the other ones. In case of the best sensitivity dataset, it was found out that QCR1A0027 had best sensitivity for all the distances when compared to the other ROSAs.

The sample-to-sample variation in receiver sensitivity is up to 6 dB, whereas the standard deviation in insertion loss was only 1 dB. We can therefore not conclude that the variation in sensitivity is due to parts of the signal and/or LO light not hitting the PDs. It must therefore be due to large variation in wavefront between signal and LO at the PD surface – a factor that can be challenging to determine with high accuracy during assembly. This indicates that achieving a high yield for the bulk implementation of the QC-ROSA could be challenging and thereby costly. Again, the advances of alignment in PIC waveguides appear to be an attractive solution.

Polarization dependence

Another important aspect of measuring the sensitivity was to analyse the variation of sensitivity due to influence of polarization over different distances of fiber. Therefore, the maximum variation in sensitivity values due to polarization is summarized for the 15 ROSAs over the different distances and presented in table 9.

ROSA	Sensitivity variation due to polarization(dB)			
	BTB	10 Km	20 Km	30 Km
QCR1A0027	2.5	0.5	3.8	1
QCR1A0028	1	0.5	1	0.5
QCR1A0029	0.5	1.7	0.5	1.5
QCR1A0030	0.6	1.8	1.2	0.7
QCR1A0031	1	0.9	0.7	0.8
QCR1A0032	0.4	0.7	0.6	X
QCR1A0036	1	1	1.3	1.2
QCR1A0038	0.5	0.4	0.2	1
QCR1A0039	0	0.6	0	0.5
QCR1A0041	0.2	0.5	1	3.5
QCR1A0042	0.8	0.4	0.4	1.4
QCR1A0043	1.7	0.7	1.7	1.2
QCR1A0044	0.1	1.1	0.8	0.9
QCR1A0046	1.4	1.8	0.3	1.5
QCR1A0047	1.3	1.2	1.6	3.5
Average	0.87	0.92	1.07	1.37

Standard Deviation	0.65	0.48	0.89	0.92
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Table 9: Maximum sensitivity variation due to polarization. X means that it does not work for that distance

From table 9, the average variation of sensitivity due to polarization is less than 1 dB for both BTB and 10 Km, however it is a bit more than 1 dB for both 20 Km and 30 Km. This applies the same for standard deviation as well, where for 20 Km and 30 Km it is on the higher side when compared to BTB and 10 Km. However, in general the polarization dependence is very close to the targeted 1.5 dB for all transmission distances. This confirms that the use of an optical isolator in in the LO path is a good solution to the high polarization dependence for the AVO QC-ROSA.

Conclusion

Measurements to characterize the QC-ROSAs, including insertion loss, frequency response, polarization dependence and receiver sensitivity for 0 km, 10 km 20 km and 30 km SSMF, were performed on the different QC-ROSAs from both suppliers.

For the AVO QC-ROSA, all measured parameters were within the requirement specifications, except polarization dependence. The high polarization dependence is due to the omission of an optical isolator in the LO path. Such component has been procured and will be included in subsequent builds from AVO.

For the Youopto QC-ROSAs, receiver sensitivity, frequency response and excess loss was within requirement specifications for 14 out of 15 received units. Polarization dependence is close to the targeted 1.5 dB in most cases, but there are specific transmission distances for 3 units that exhibit a higher than specified polarization dependence.

In general, the fundamental optical and mechanical design have been proven, and the performance can be considered better than expected for the alpha prototypes. It has, however, become clear that achieving a sufficiently good optical alignment during assembly to achieve a low polarization dependence can be a challenge, and potentially lead to low yield in production.

The optical design of the AVO build – once an LO isolator has been fitted should in theory be more robust towards optical misalignment than the Youopto design. At the time of writing this

report, we have, however, only received a single prototype from AVO. It is therefore not possible at this stage to draw any conclusions on potential yield of the AVO design.

In addition to this, the target reach of 20 km at 25 Gbps has been increased to 30 km due to advances in ASIC design.

Appendices

A. Results of ROSA-QCR1A0028

A.1 Frequency Sweep

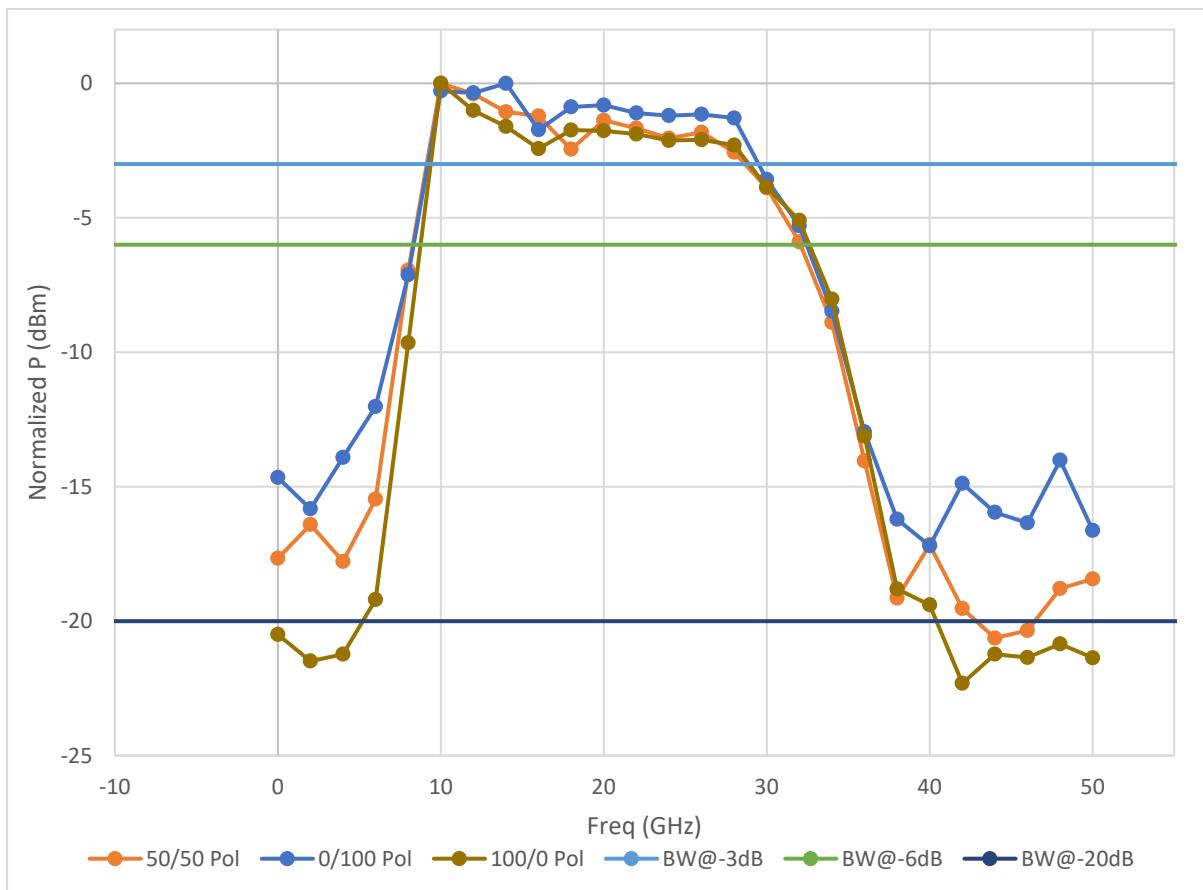


Figure.79.Frequency.sweep.for.ROSA.QCR7A6684_Signal.Power.±.86.dBm?gain.±.9;60V

A.2 Sensitivity

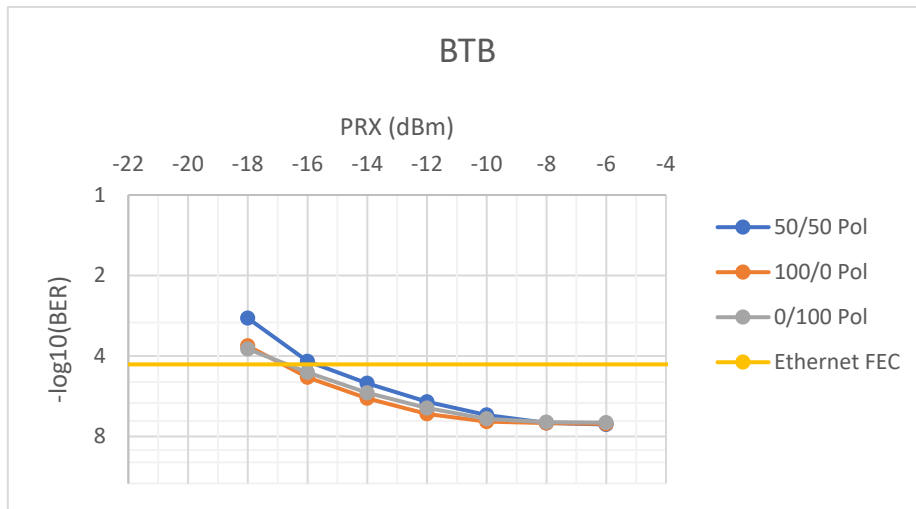


Figure.70 Sensitivity curve ROSA_QCR7A6684 for BTB with IF \pm 97 GHz



Figure.71 Sensitivity curve ROSA_QCR7A6684 for 76 Km with IF \pm 96 GHz

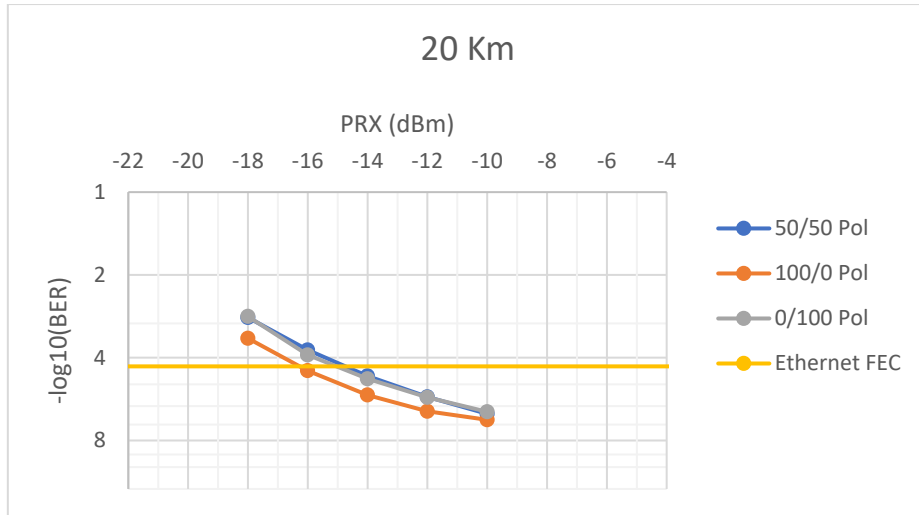


Figure.7 Sensitivity curve ROSA_QCR7A668 for 86.Km with IF \pm 8 GHz

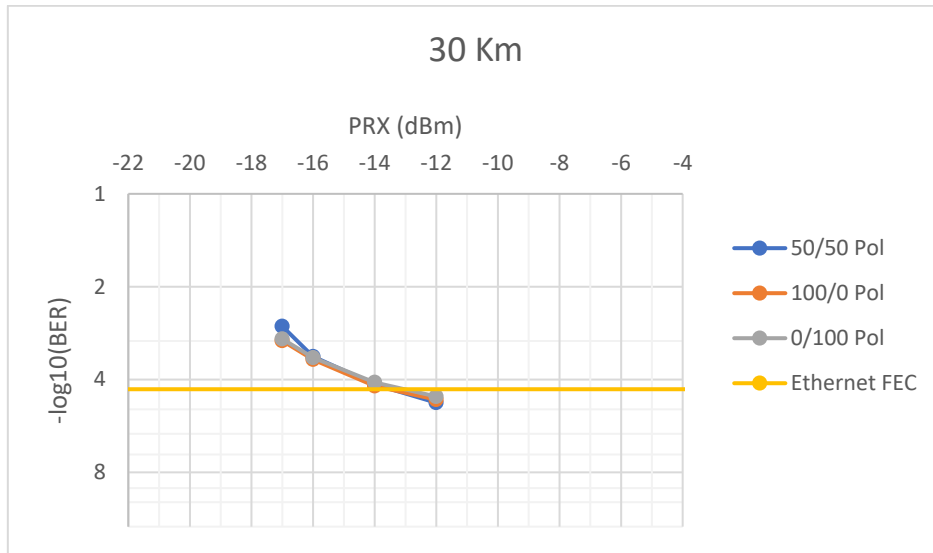


Figure.7 Sensitivity curve ROSA_QCR7A668 for 96.Km with IF \pm 97 GHz

B. Results of ROSA-QCR1A0029

B.1 Frequency Sweep

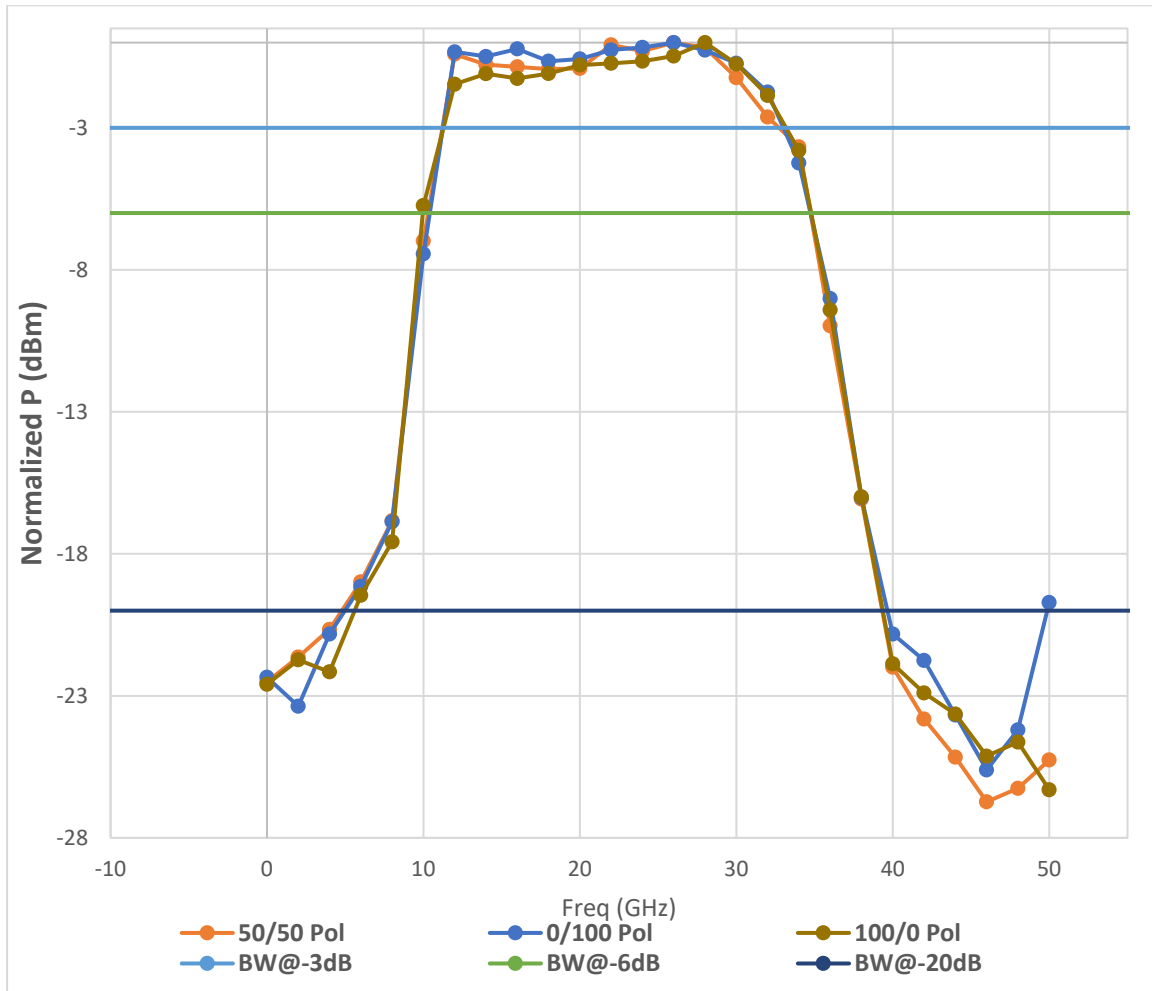


Figure.7 Frequency sweep for the ROSA-QCR7A668 Signal Power \pm .86 dBm?gain \pm .9j6V

B.2 Sensitivity

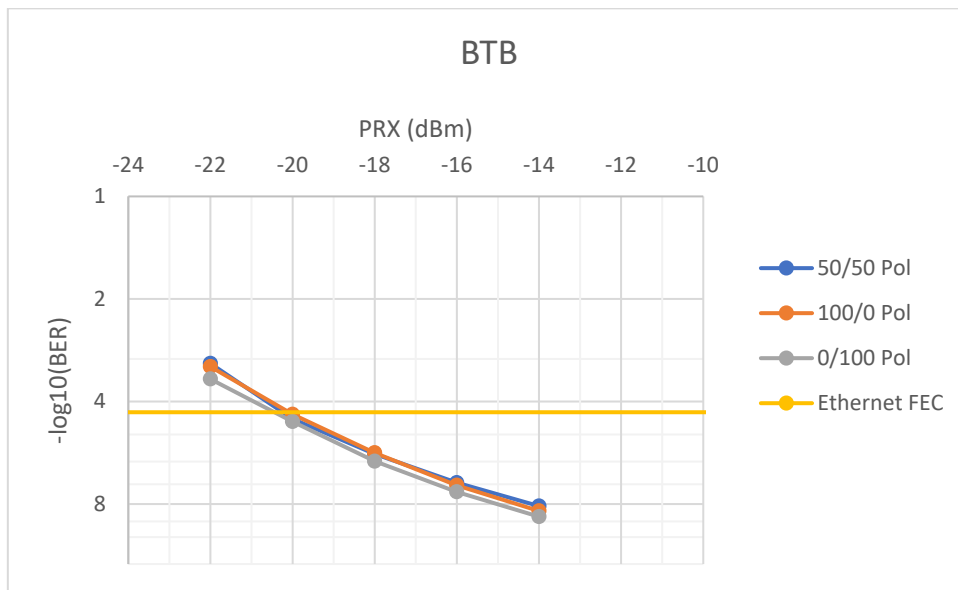


Figure.76.Sensitivity.for.ROSA_QCR7A668for.BTB.with.IF.±.98.GHz

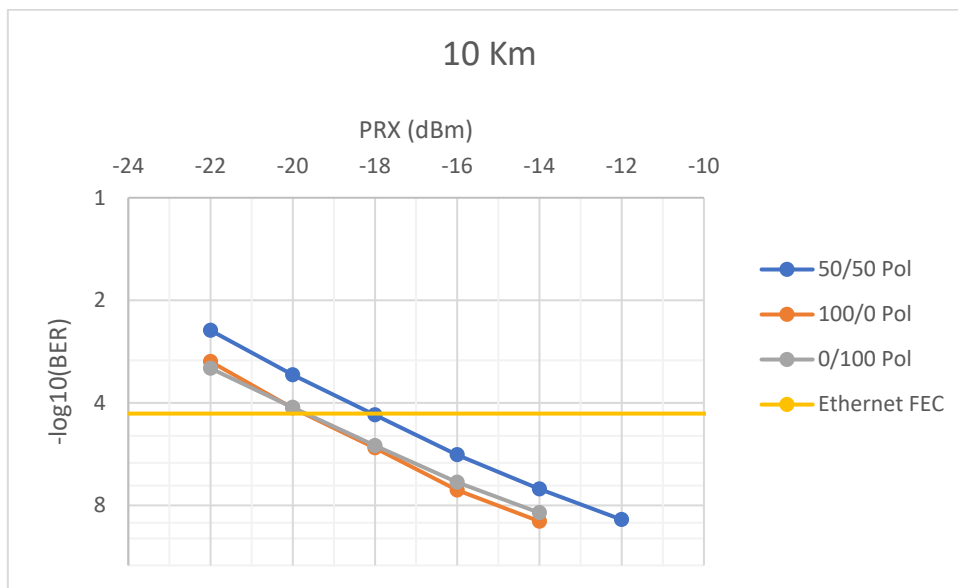


Figure.86.Sensitivity.for.ROSA_QCR7A668for.76.Km.with.IF.±.98.GHz

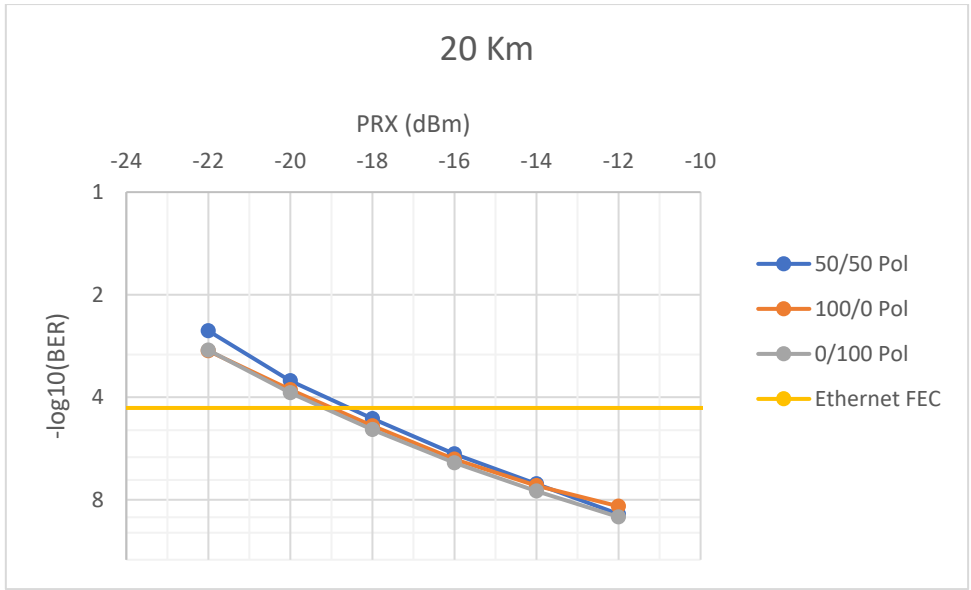


Figure.87.Sensitivity.for.ROSA_QCR7A668 for.86.Km.with.IF.±.8GHz

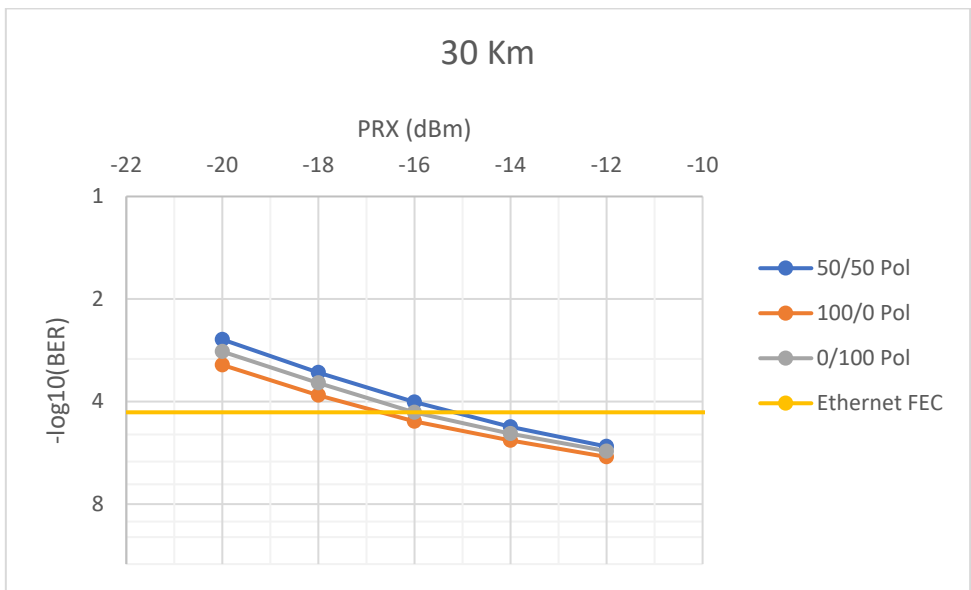


Figure.88.Sensitivity.curve.ROSA_QCR7668 for.96.Km.with.IF.±.8GHz

C. Results of ROSA-QCR1A0036

C.1 Frequency Sweep

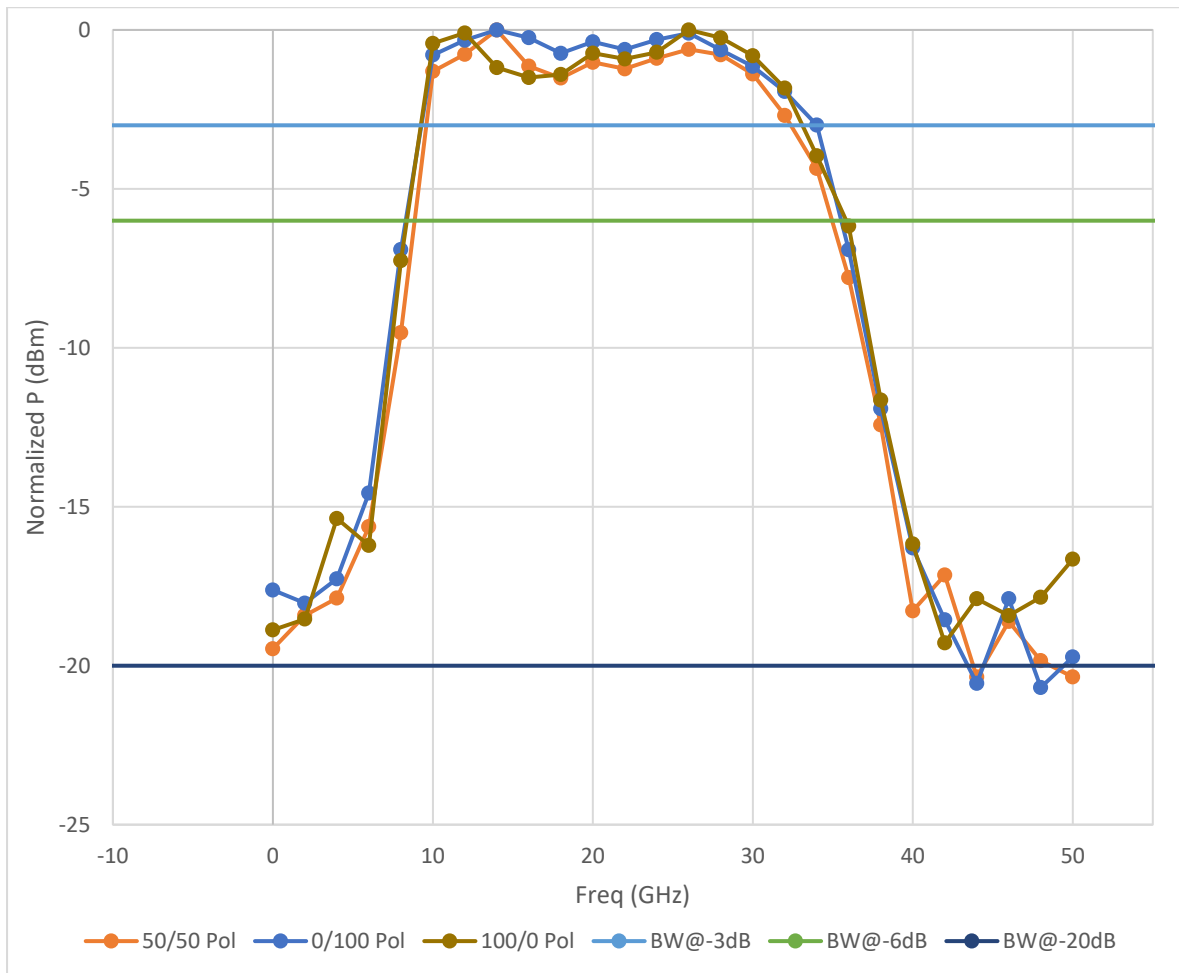


Figure.89.Frequency.sweep.for.the.ROSA_QCR7A669@_Signal.power.±.86.dBm?gain.±.9;6@V

C.2 Sensitivity

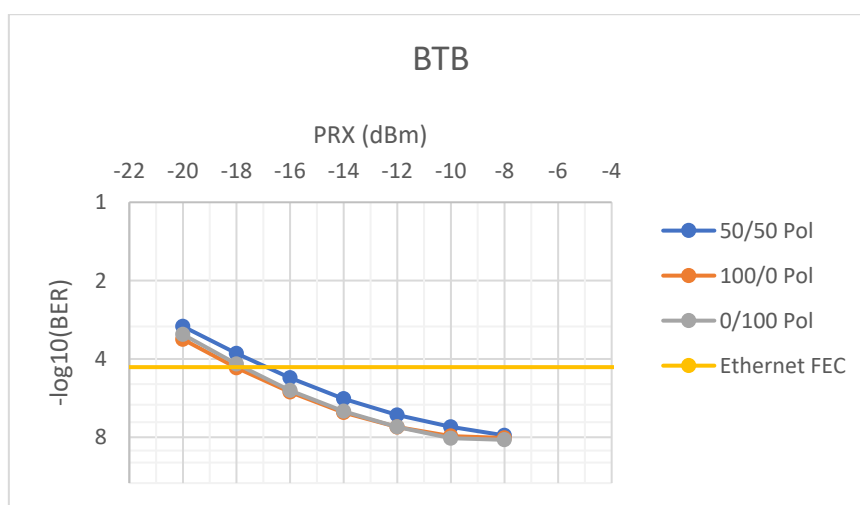


Figure.80.Sensitivity.curve.for.ROSA_QCR7A669@for.BTB.with.IF.±.98.GHz

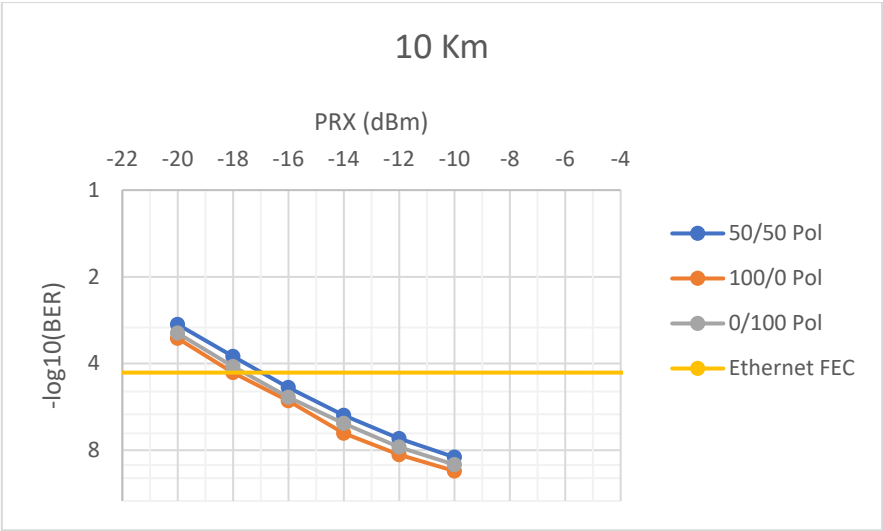


Figure.80 Sensitivity curve ROSA_QCR7A669 for 76 Km with IF ± 98 GHz



Figure.82 Sensitivity curve ROSA_QCR7A669 for 86 Km with IF ± 8 GHz

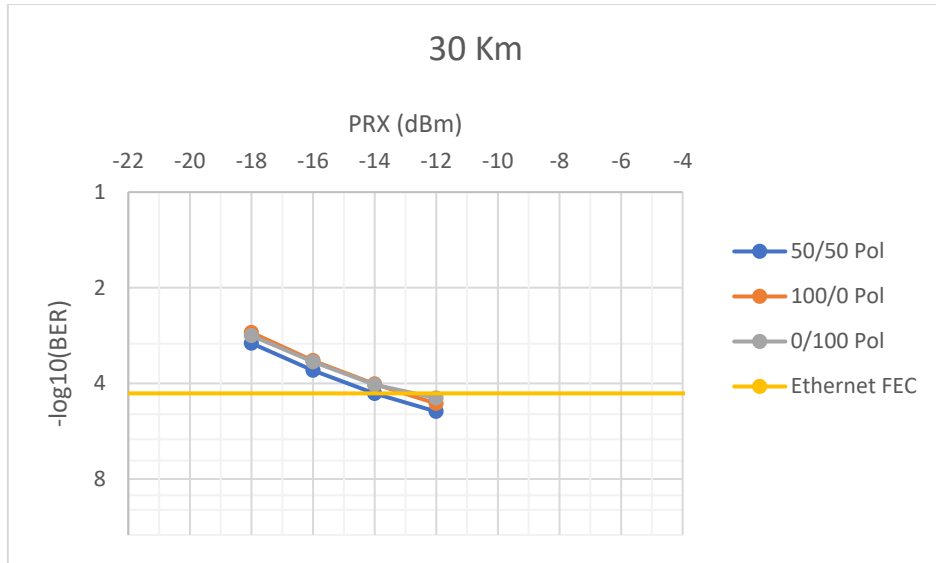


Figure.8 Sensitivity curve ROSA_QXR7A669 for 96 Km with IF \pm 8 GHz

D. Results of ROSA-QCR1A0038

D.1 Frequency Sweep

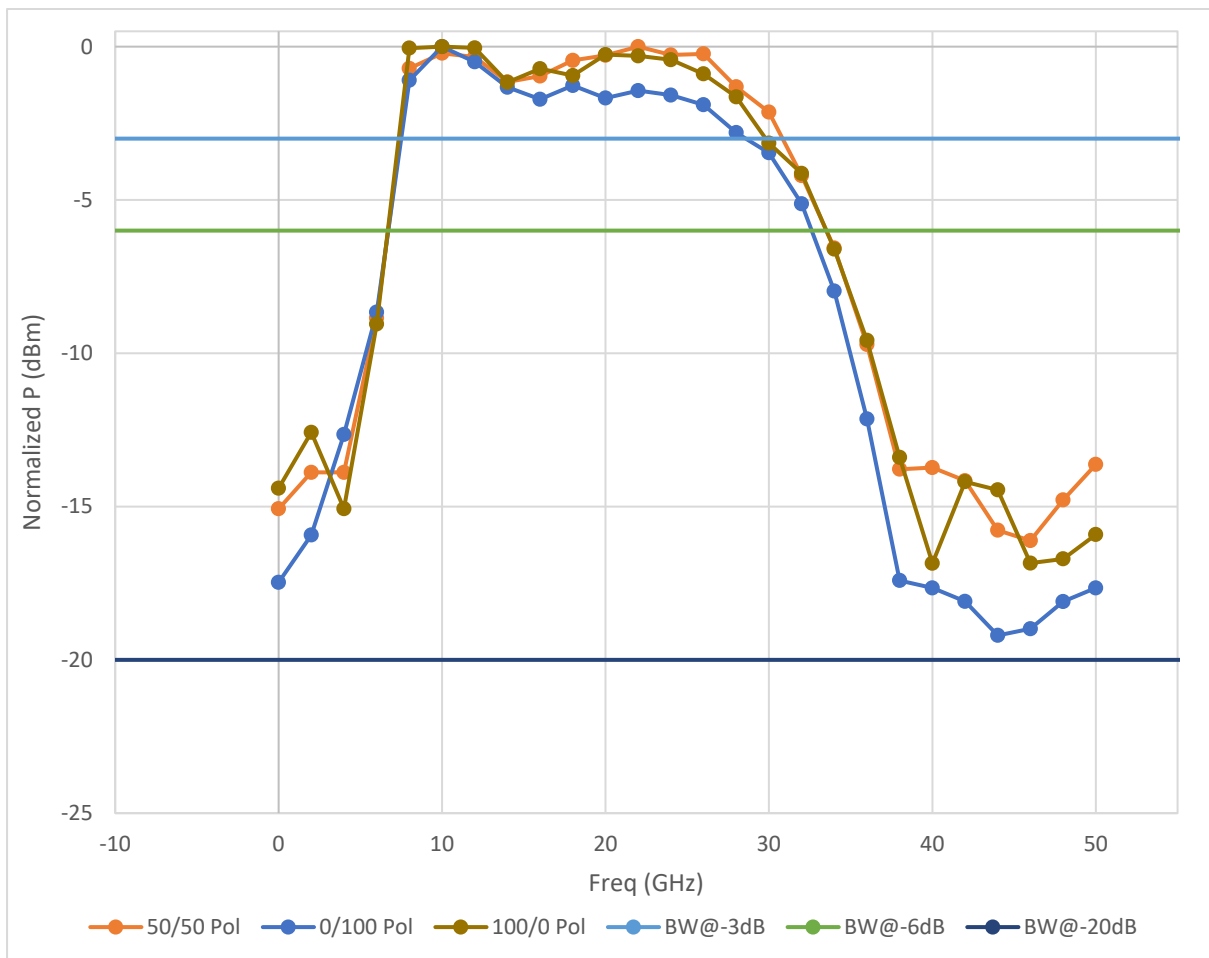


Figure.8 Frequency sweep for ROSA_QCR7A669 Signal power \pm 86 dBm gain \pm 9.6 V

D.2 Sensitivity

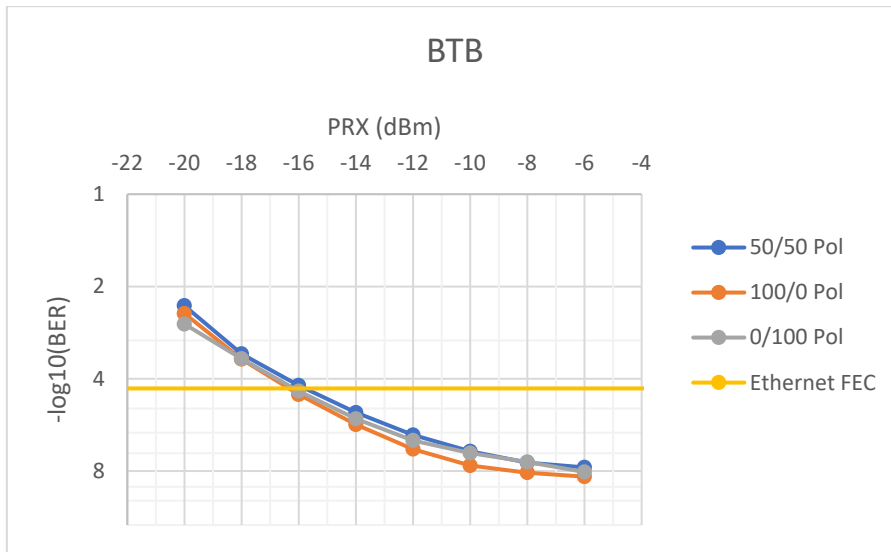


Figure.86.Sensitivity.curve.ROSA_QCR7A6694for.BTB.with.IF.±.96.GHz

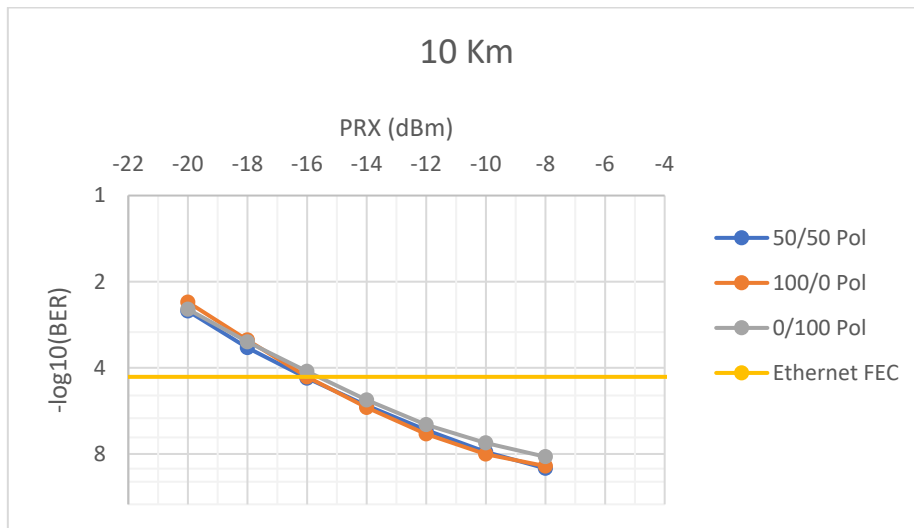


Figure.96.Sensitivity.curve.ROSA_QCR7A6694for.BTB.with.IF.±.96.GHz

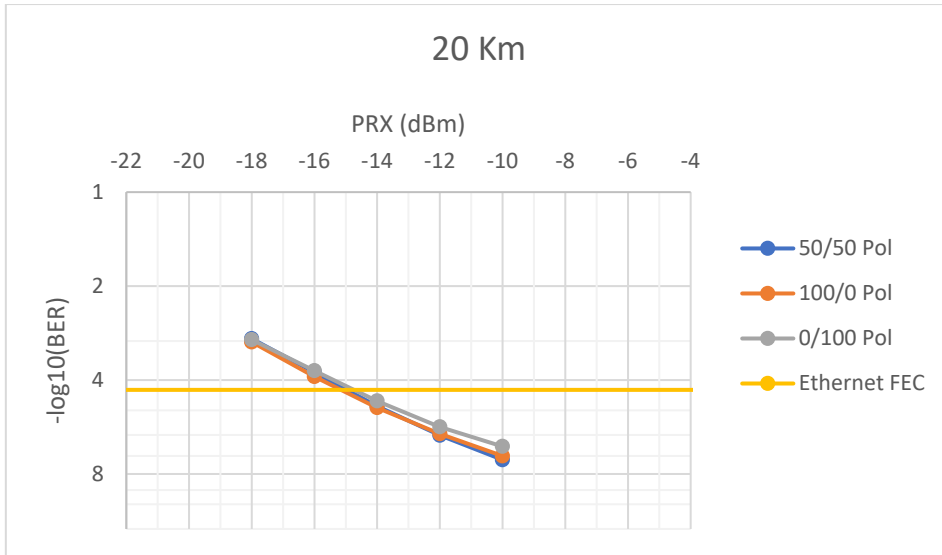


Figure.97.Sensitivity.curve.ROSA_QCR7A6694for.86.Km.with.IF.±.8GHz

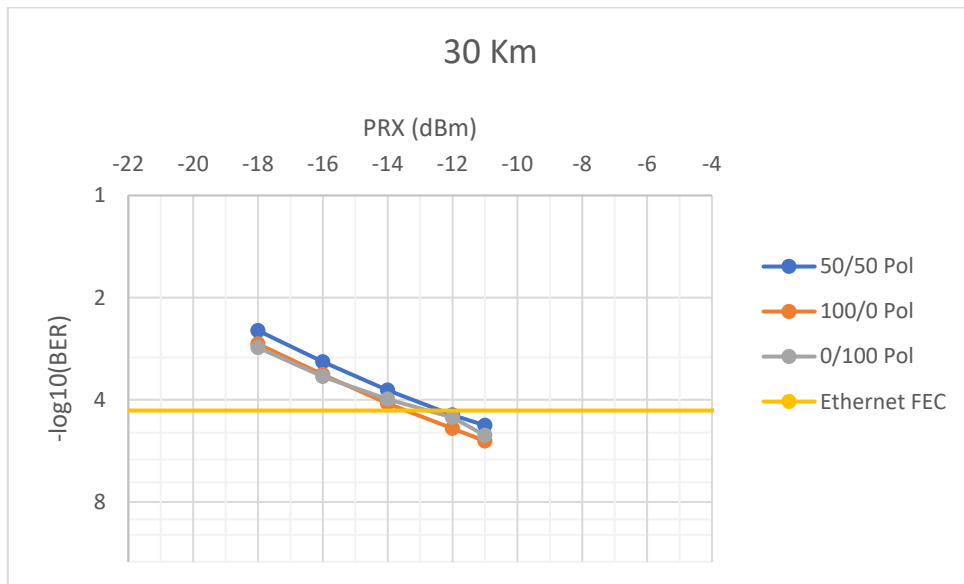


Figure.98.Sensitivity.curve.ROSA_QCR7A6694for.96.Km.with.IF.±.8GHz

E. Results of ROSA-QCR1A0041

E.1 Frequency Sweep

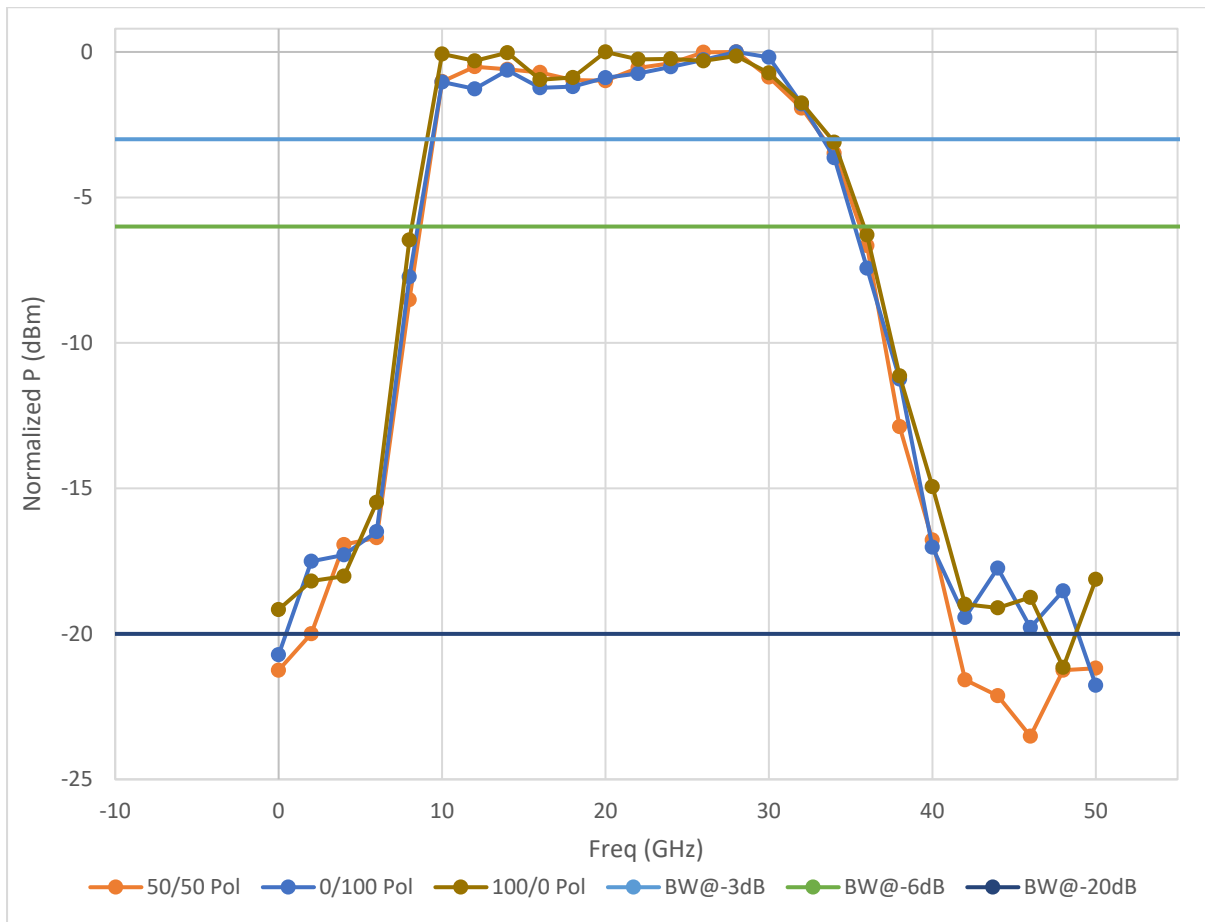


Figure.99.Frequency.sweep.for.the.ROSA_QCR7A6607_Signal.power.±.86.dBm?gain.±.9j62V

E.2 Sensitivity

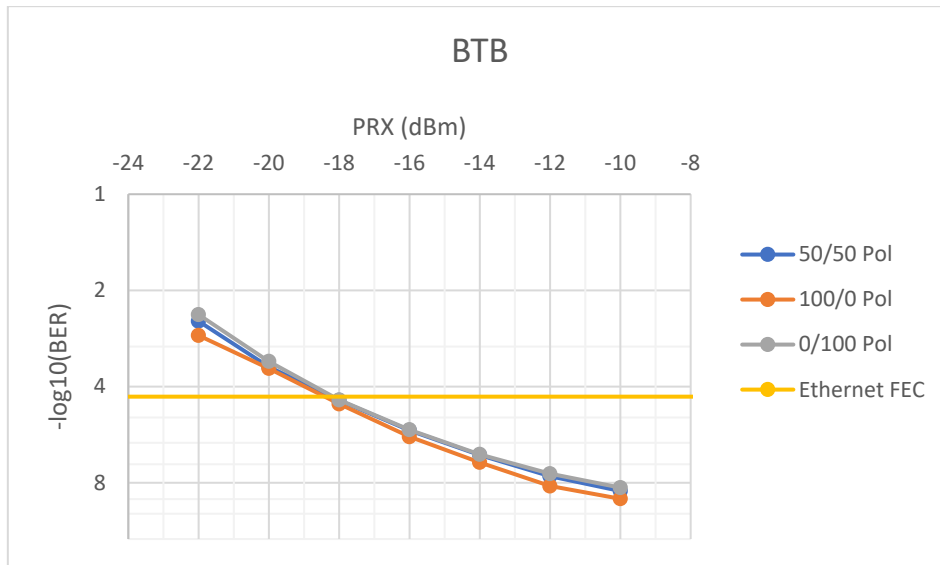


Figure.90.Sensitivity.curve.ROSA_QCR7A6607.for.BTB.with.IF.±.99.GHz



Figure.91.Sensitivity.curve.ROSA_QCR7A6607.for.76.Km.with.IF.±.96.GHz

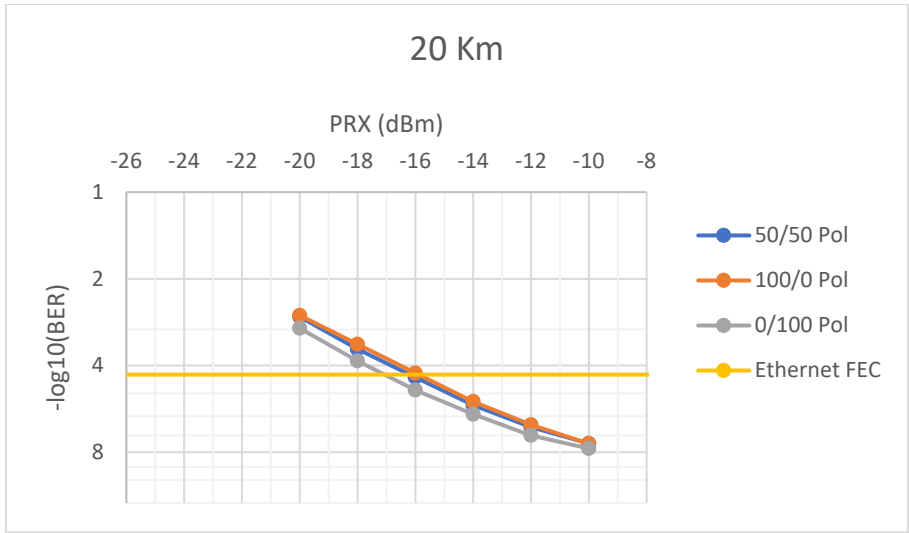


Figure.9.9 Sensitivity curve ROSA_QCR7A6607 for 86 Km with IF ± 80 GHz

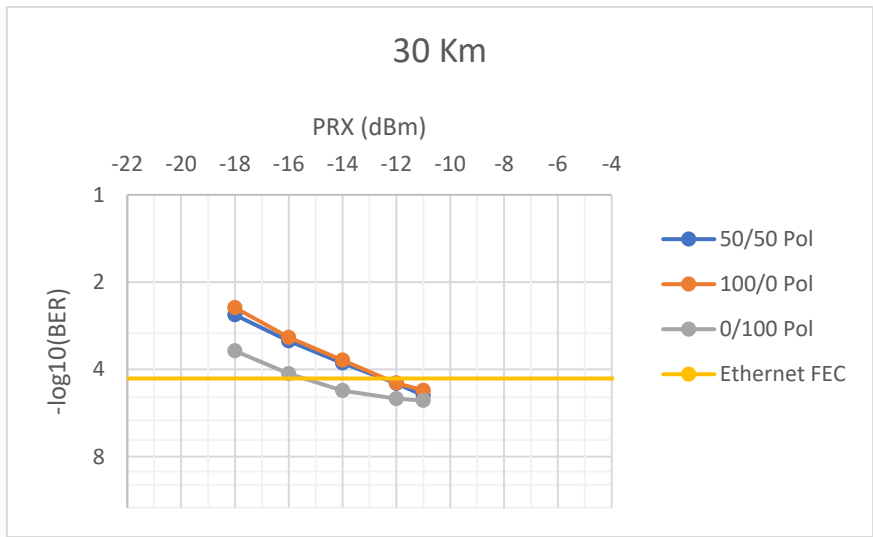


Figure.9.10 Sensitivity curve for ROSA_QCR7A6607 for 96 Km with IF ± 80 GHz

F. Results of ROSA-QCR1A0030

F.1 Frequency Sweep

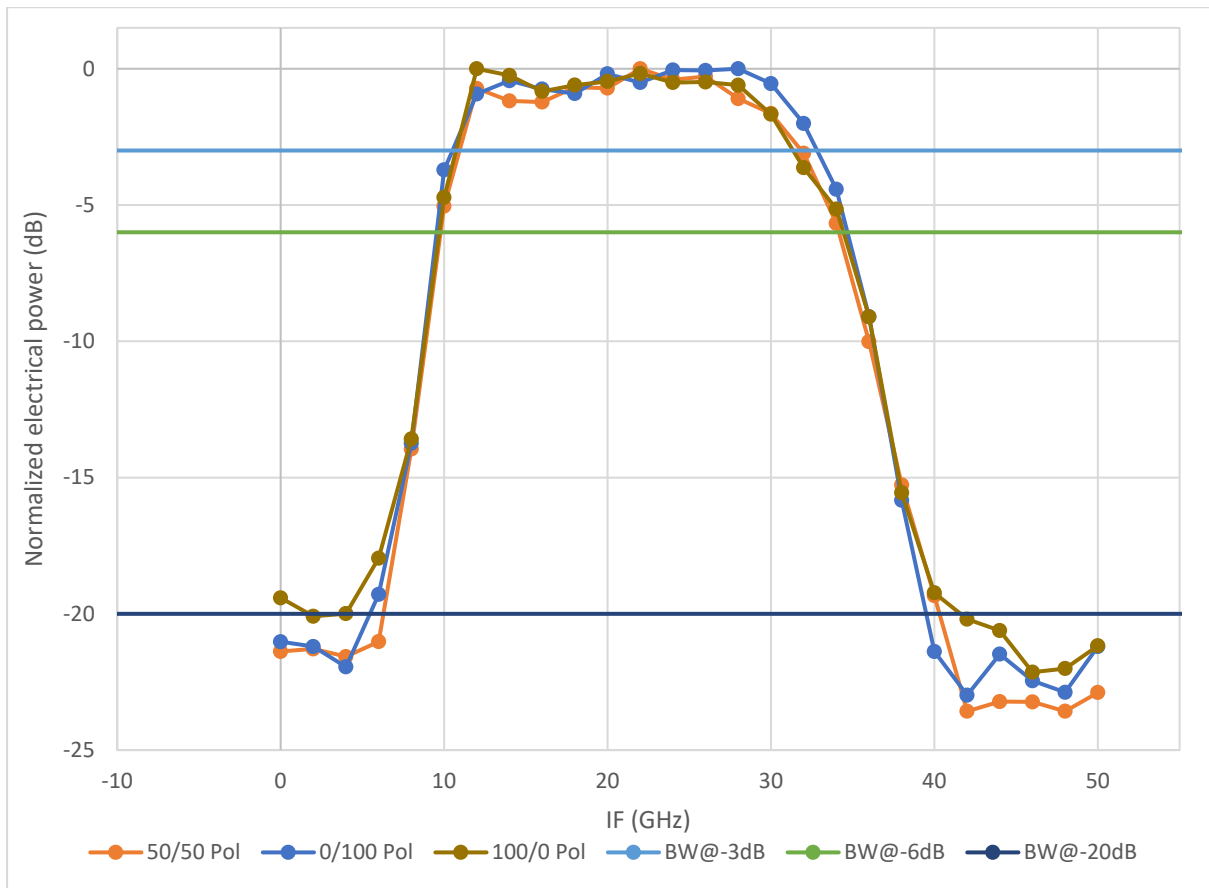


Figure.9.9 Frequency sweep for ROSA_QCR7A6696_Signal.power.±.86.dBm?gain.±.9;6.2V

F.2 Sensitivity

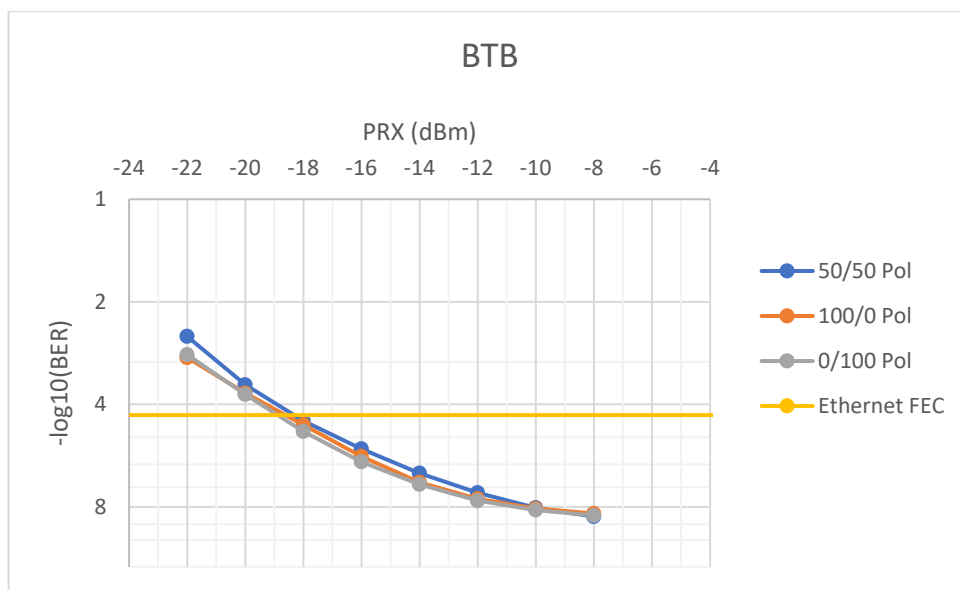


Figure.9.10 Sensitivity curve for ROSA_QCR7A6696 for BTB with IF.±.97.GHz

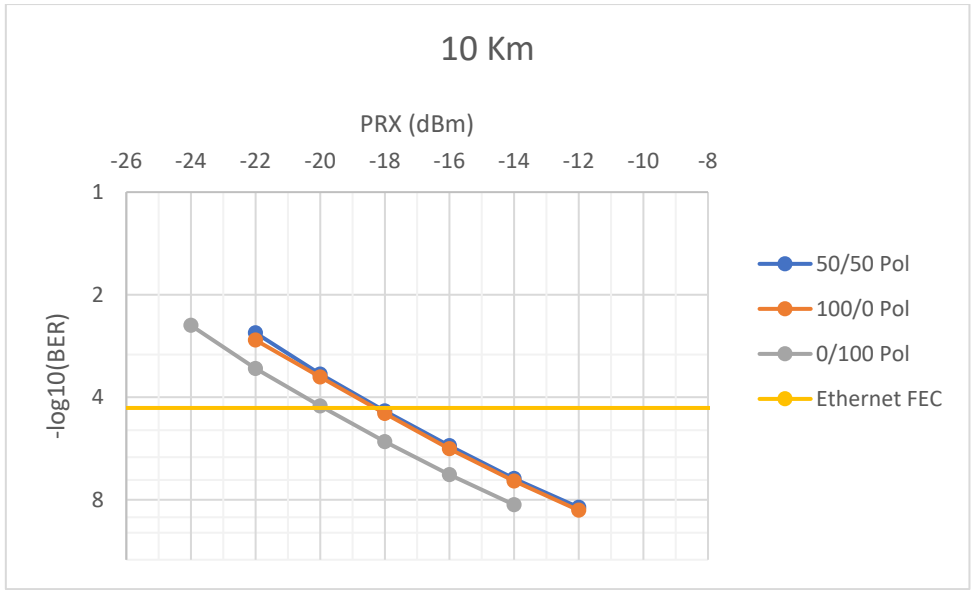


Figure.06.Sensitivity.curve.ROSA_QCR7A6696.for.76.Km.with.IF.±.97.GHz

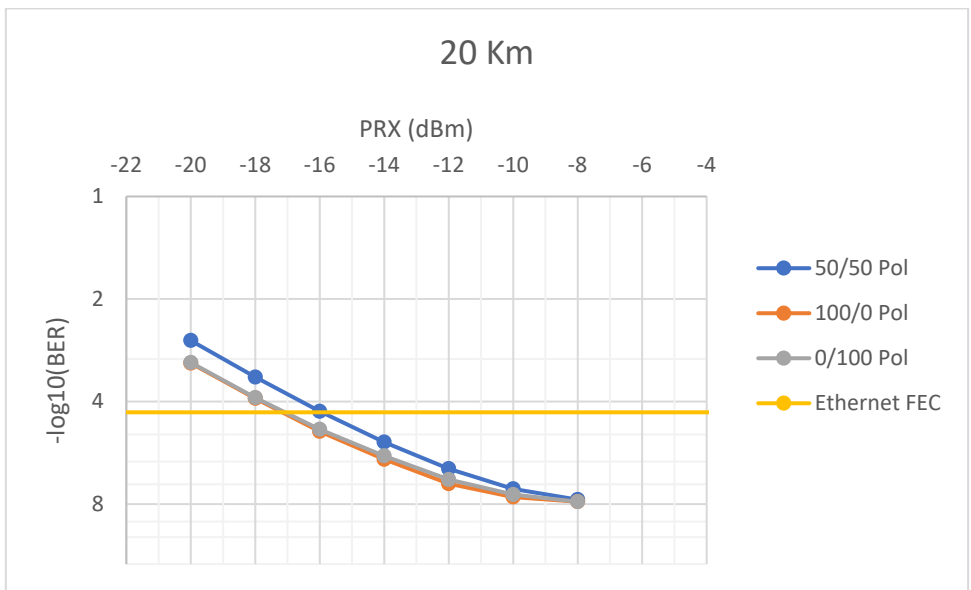


Figure.07.Sensitivity.curve.ROSA_QCR7A6696.for.86.Km.with.IF.±.98.GHz



Figure.08.Sensitivity.curve.ROSA_QCR7A6696.for.96.Km.with.IF.±.90GHz

G. Results of ROSA-QCR1A0031

G.1 Frequency Sweep

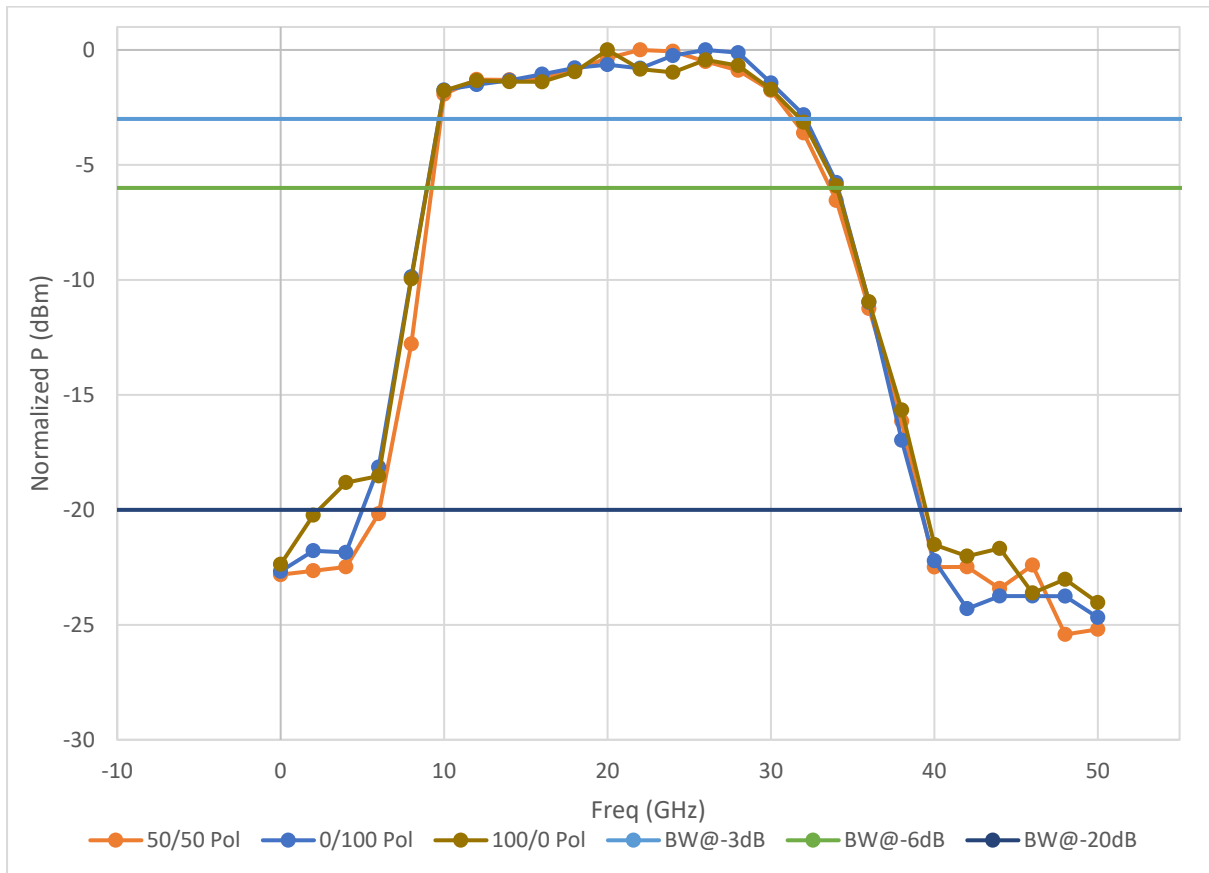


Figure.09.Frequency.sweep.for.ROSA_QCR7A6697_Signal.power.±.88.dBm?gain.±.9;60V

G.2 Sensitivity

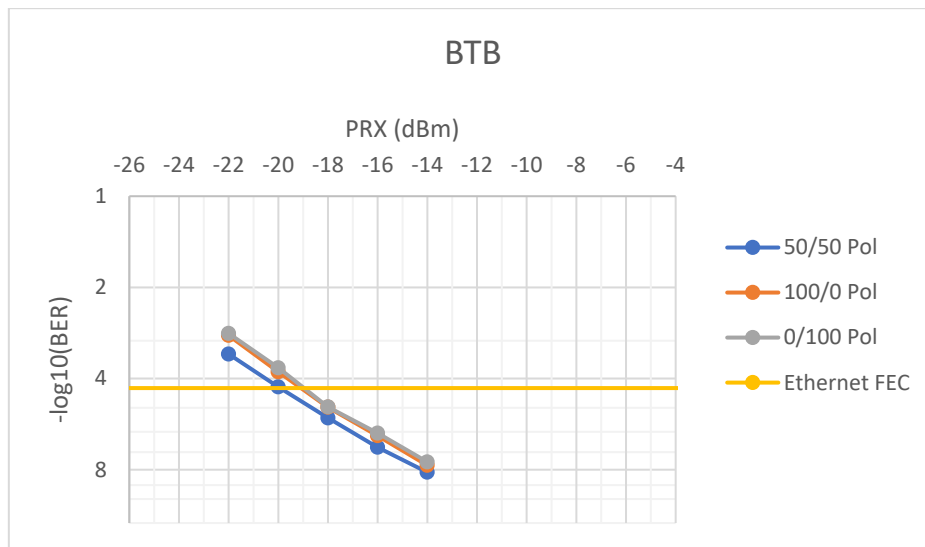


Figure.00.Sensitivity.curve.ROSA_QCR7A6697.for.BTB.with.IF±_97.GHz

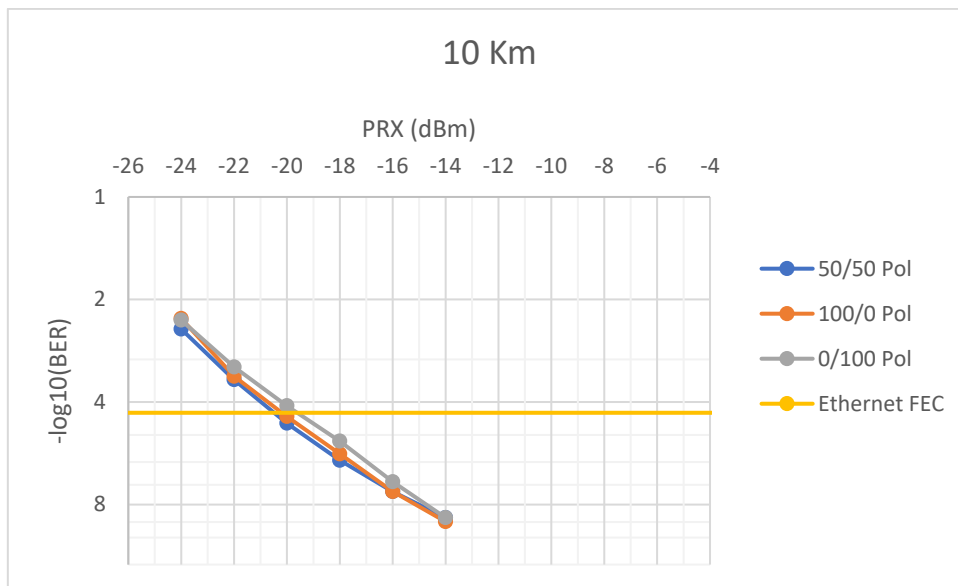


Figure.01.Sensitivity.curve.ROSA_QCR7A6697.for.76.Km.with.IF±_96.GHz

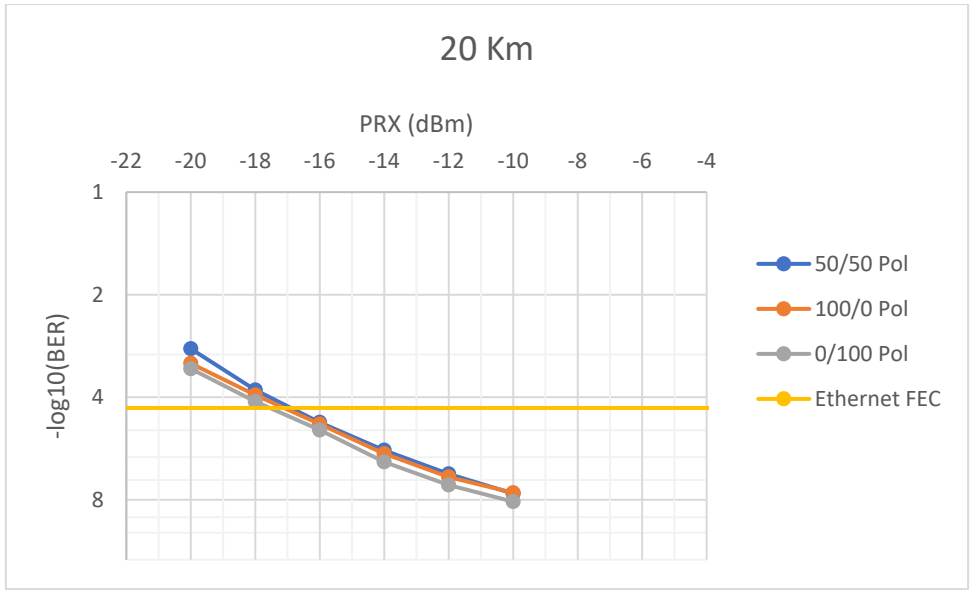


Figure.00 Sensitivity curve ROSA_QCR7A6697 for 86 Km with IF ± 8 GHz



Figure.00 Sensitivity curve for ROSA_QCR7A6697 for 96 Km with IF ± 8 GHz

H. Results of ROSA-QCR1A0032

H.1 Frequency Sweep

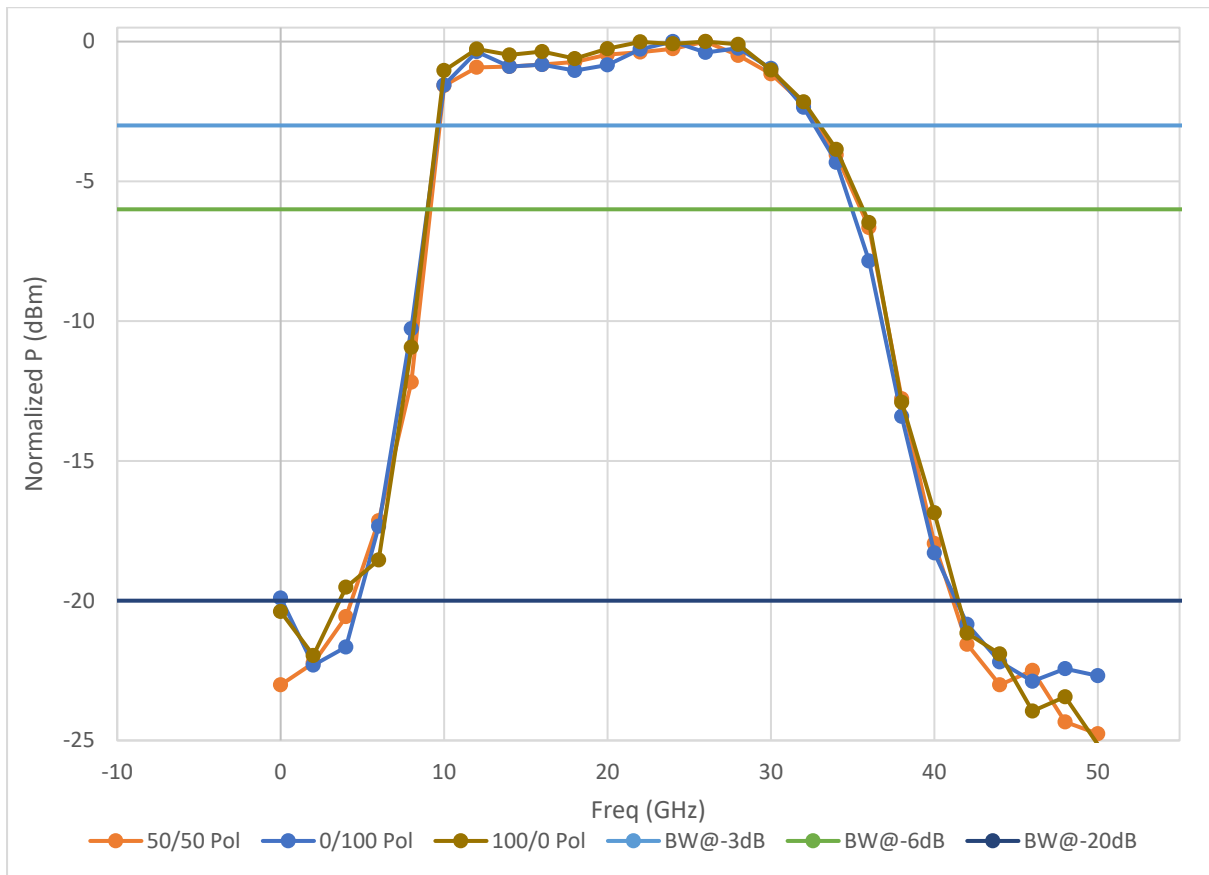


Figure 004 Frequency sweep of ROSA_QCR7A6698_Signal.power.±_86.dBm?gain.±_9;6

H.2 Sensitivity

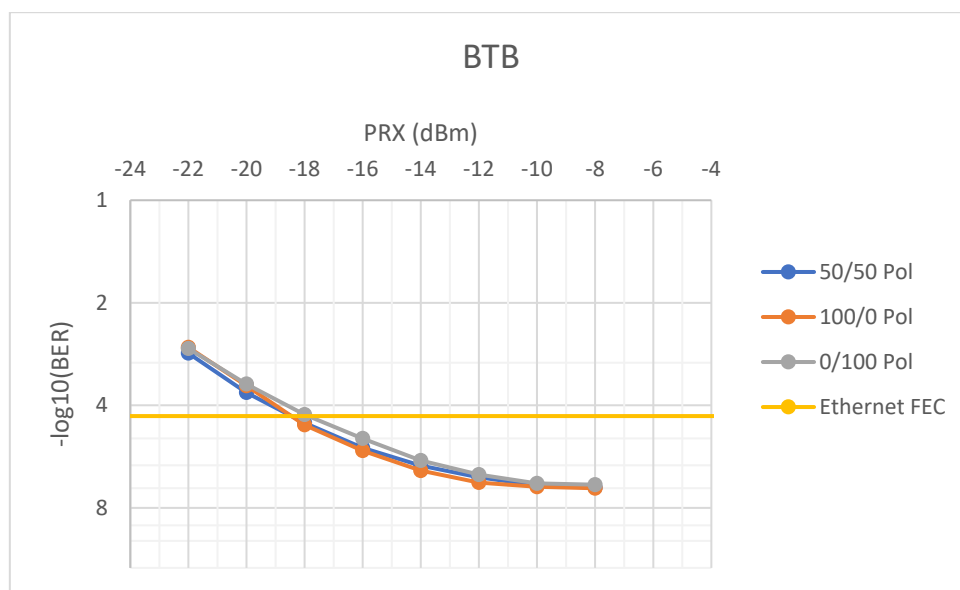


Figure 005 Sensitivity curve ROSA_QCR7A6698 for BTB with IF.±_98.GHz

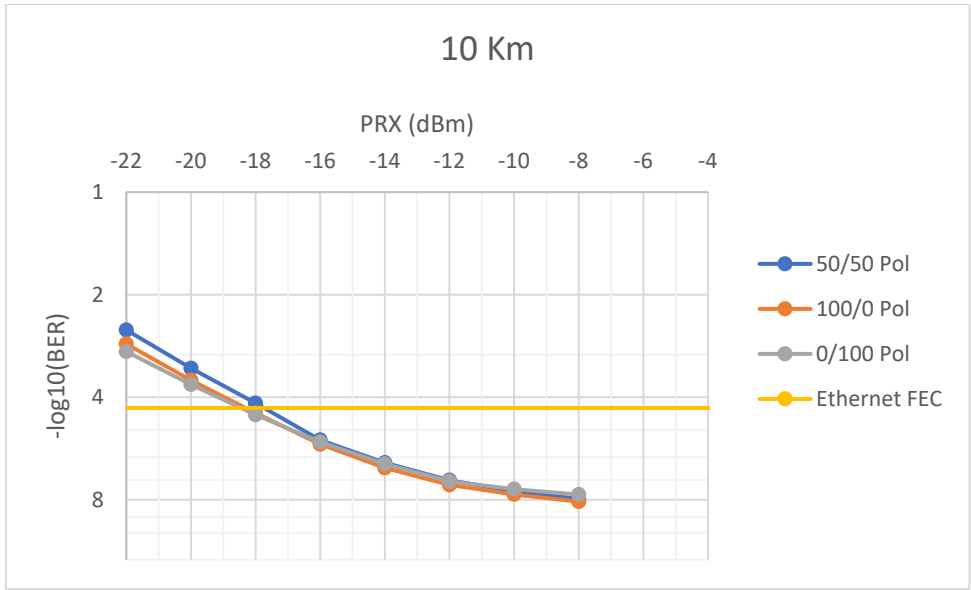


Figure.06.Sensitivity.curve.ROSA_QCR7A6698.for.76.Km.with.IF.±.98.GHz

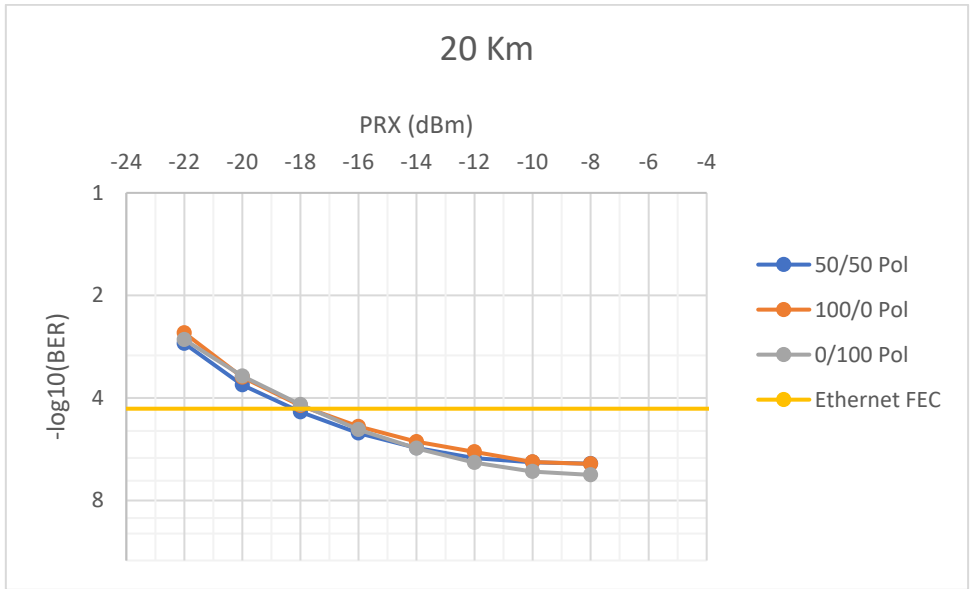


Figure.07.Sensitivity.curve.ROSA_QCR7A6698.for.86.Km.with.IF.±.99.GHz

I. Results of ROSA-QCR1A0039

I.1 Frequency Sweep

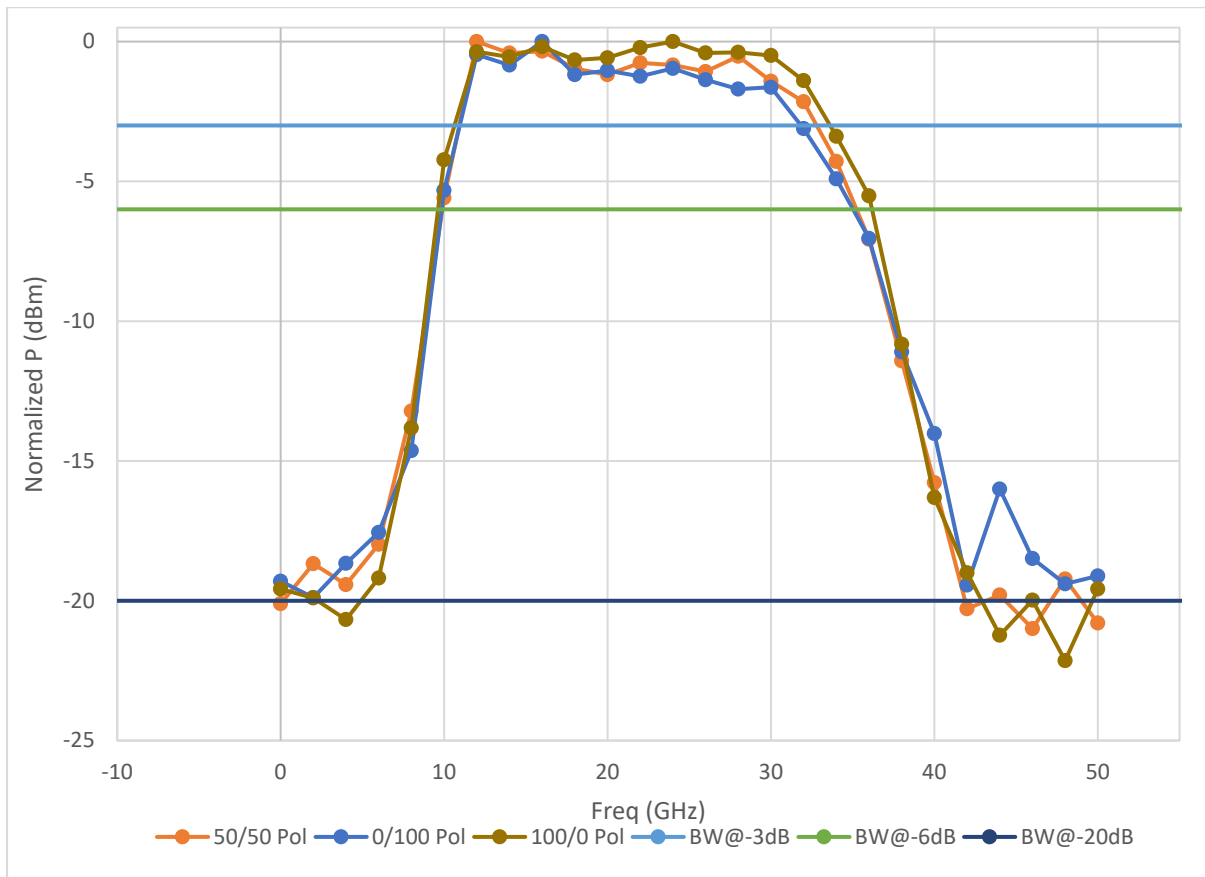


Figure.03.Frequency.sweep.for.ROSA_QCR7A6696.Signal.Power.±.86.dBm?gain.±.9;6@V

I.2 Sensitivity

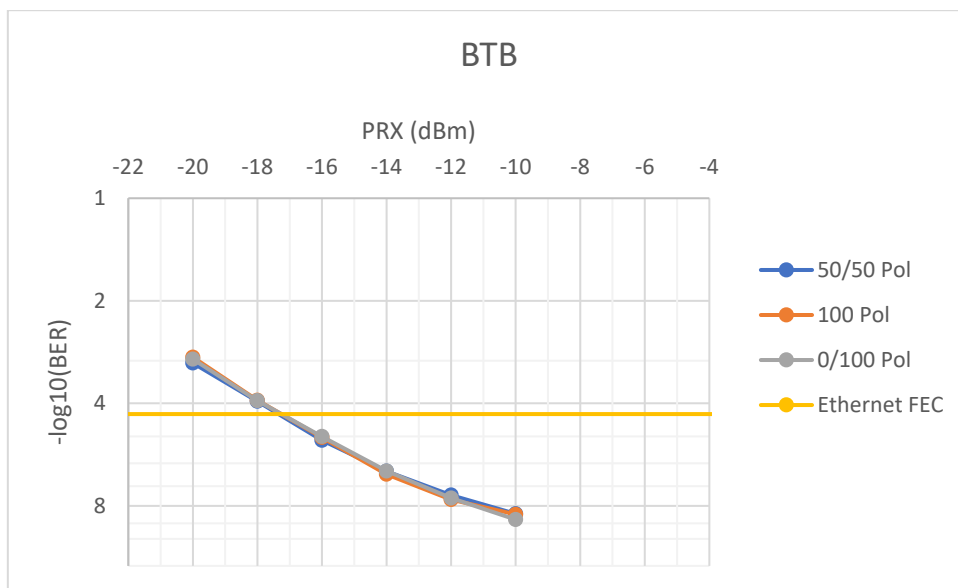


Figure.09.Sensitivity.curve.ROSA_QCR7A6696.for.BTB.with.IF.±.99.GHz

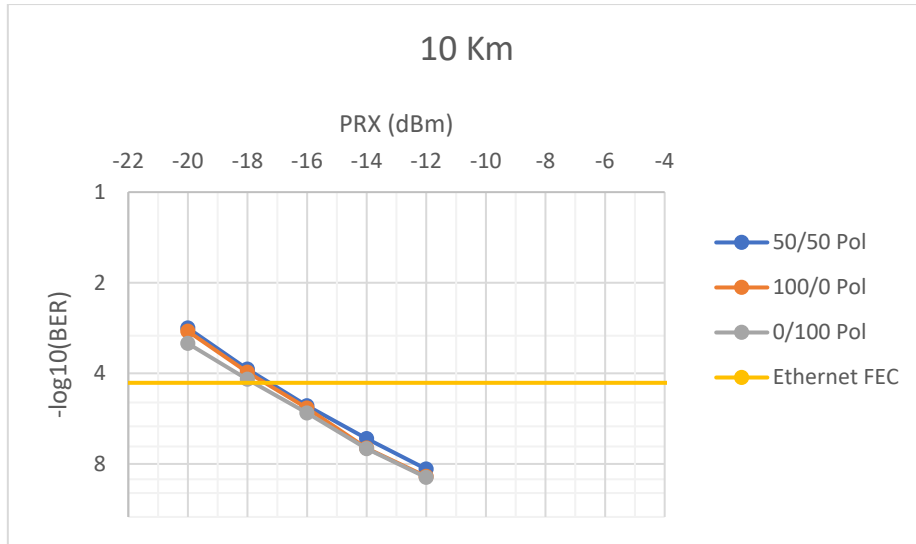


Figure 10 Sensitivity curve ROSA_QCR7A6695 for 76 Km with IF ± 99 GHz



Figure 10 Sensitivity curve ROSA_QCR7A6695 for 86 Km with IF ± 89 GHz

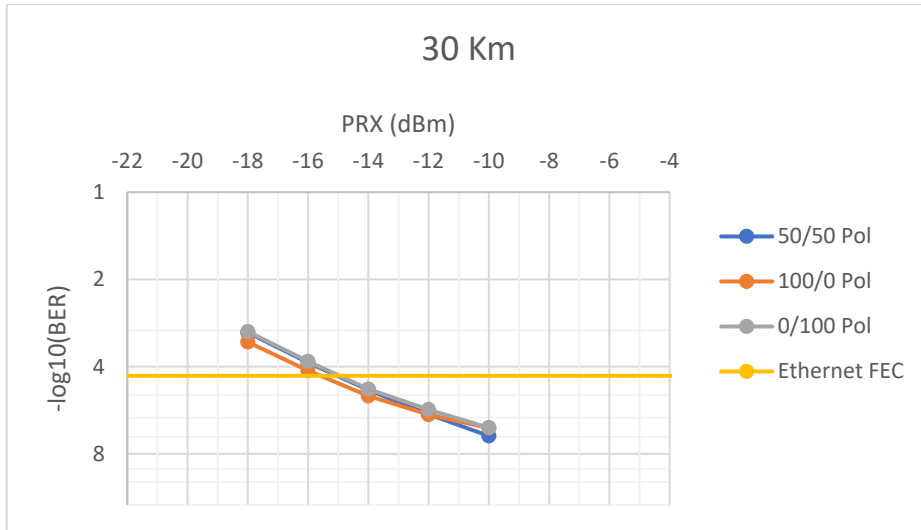


Figure 12 Sensitivity curve ROSA_QCR7A6696 for 96 Km with IF ± 99 GHz

J. Results of ROSA-QCR1A0042

J.1 Frequency Sweep

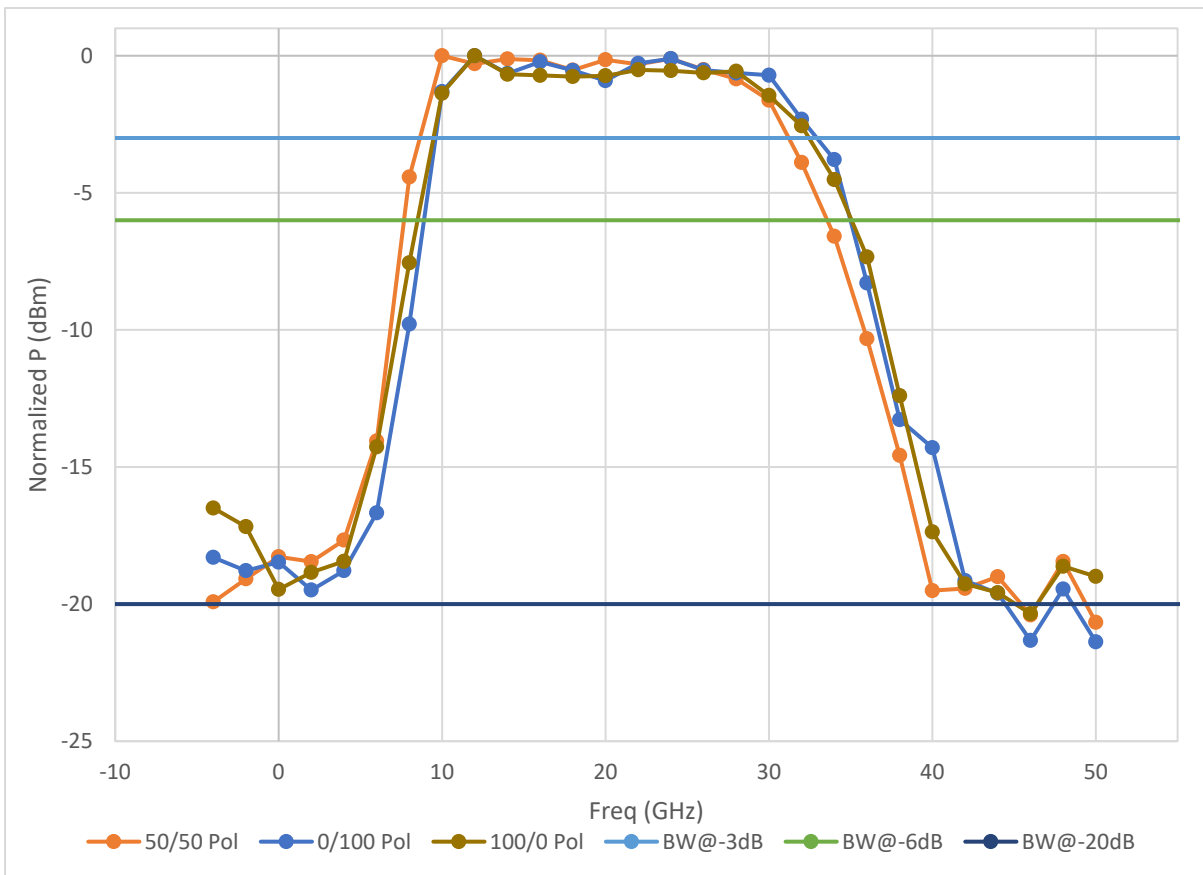


Figure 13 Frequency sweep for ROSA_QCR7A6608? Signal power ± 86 dBm? gain ± 9j6

J.2 Sensitivity

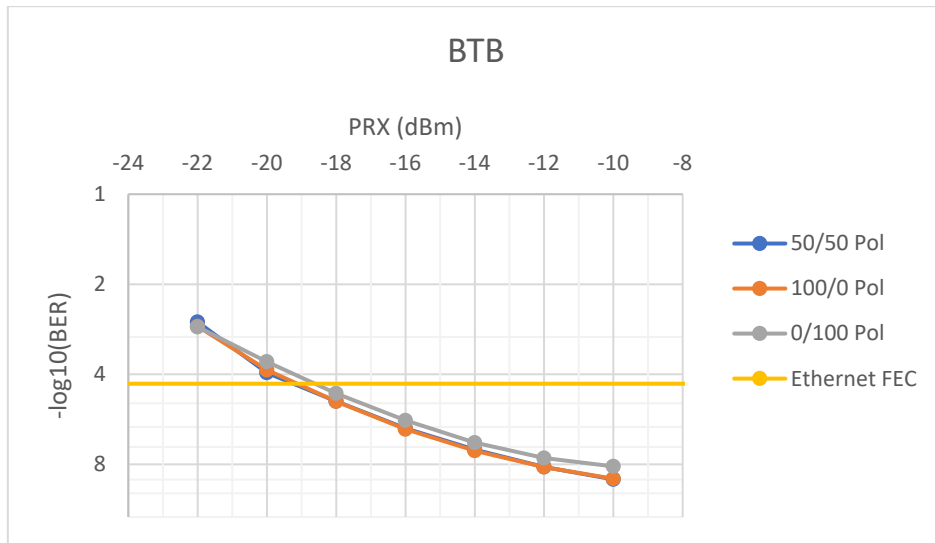


Figure. 14 Sensitivity curve ROSA_QCR7A6608 for BTB with IF ± 98 GHz

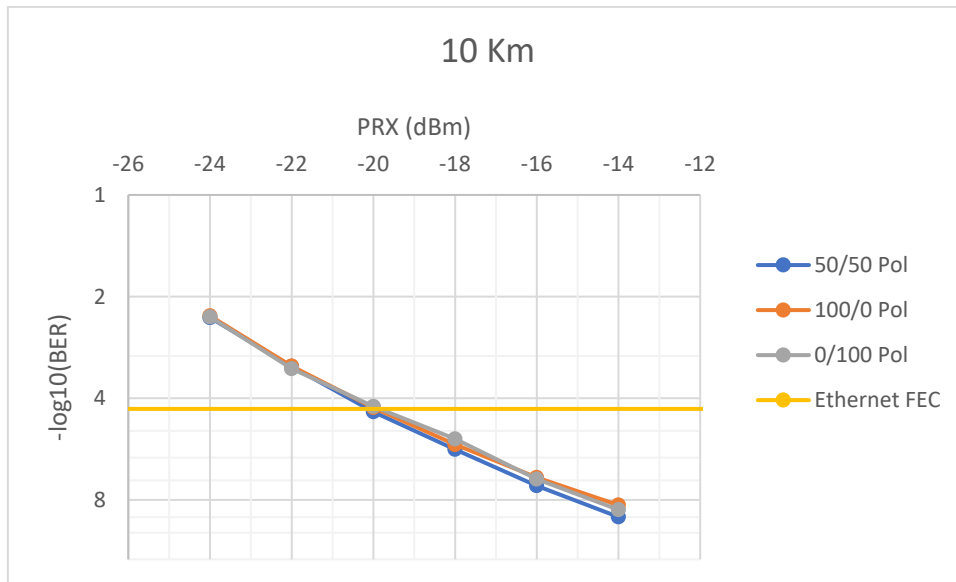


Figure. 15 Sensitivity curve ROSA_QCR7A6608 for 76 Km with IF ± 96 GHz

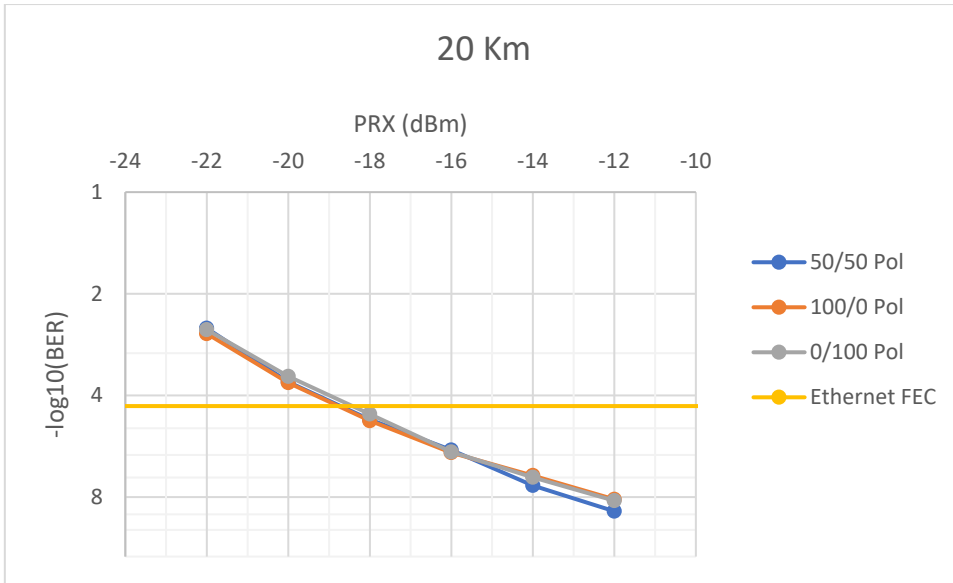


Figure.26.Sensitivity.curve.for.ROSA_QCR7A6608.for.86.Km.with.IF.±.80.GHz

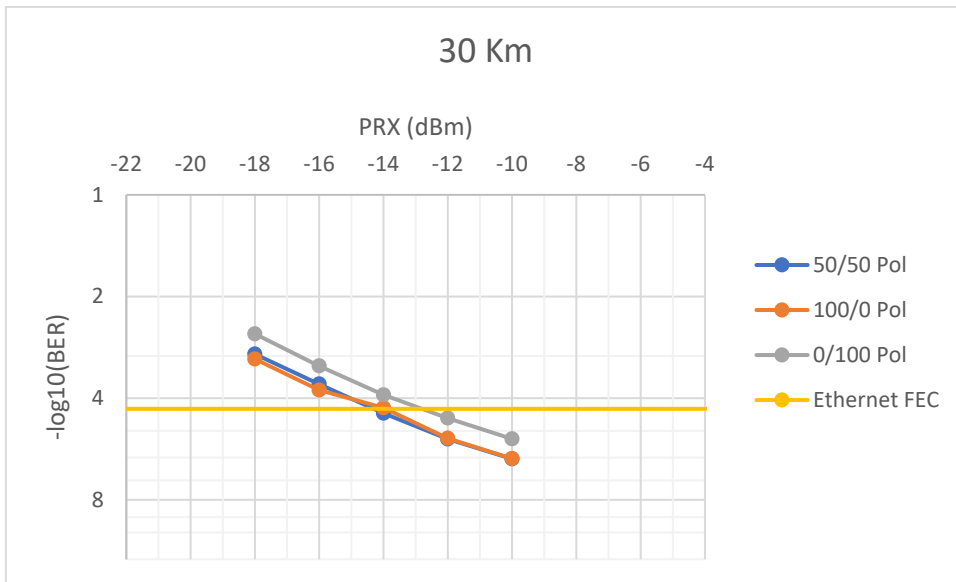


Figure.27.Sensitivity.curve.ROSA_QCR7A6608.for.96.Km.with.IF.±.80.GHz

K. Results of ROSA-QCR1A0043

K.1 Frequency Sweep

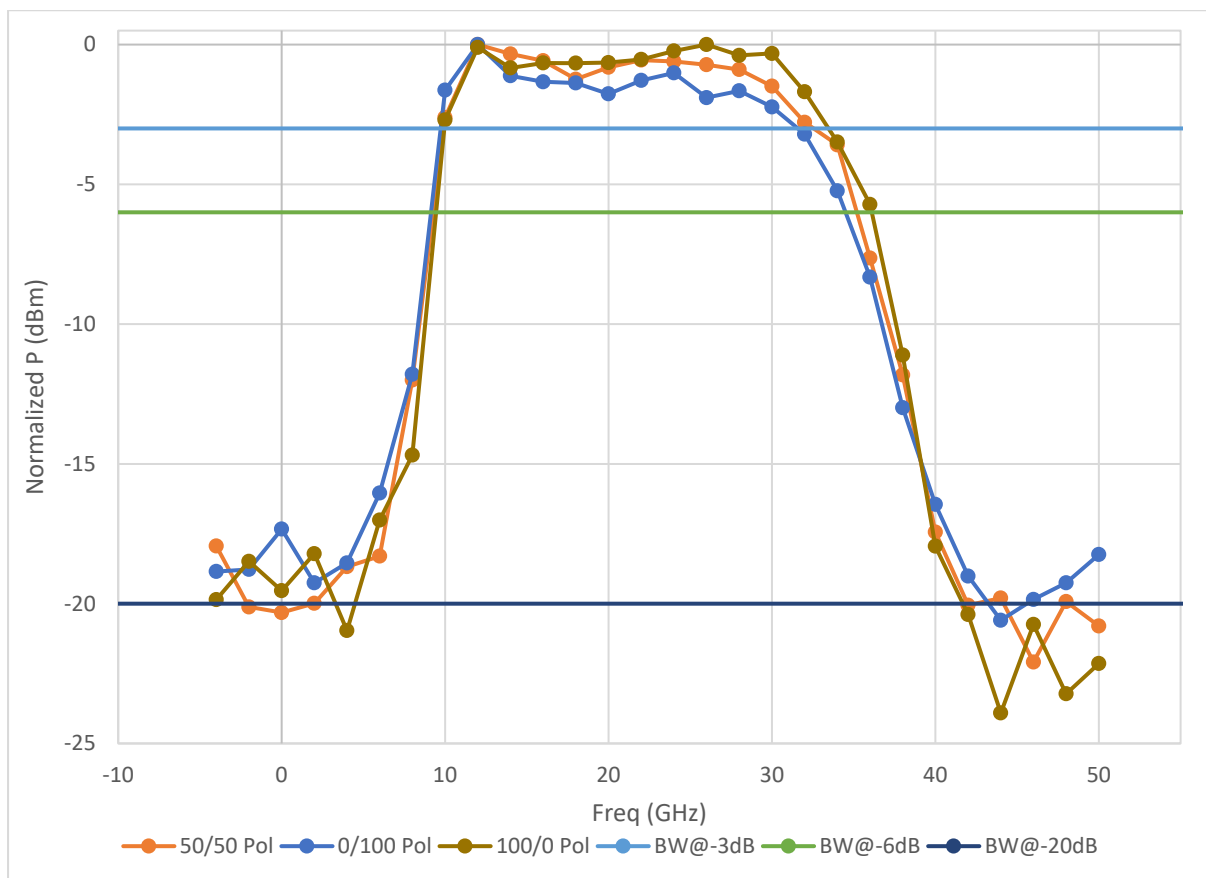


Figure 28. Frequency sweep for ROSA_QCR7A6609? Signal power ±.86 dBm? gain ±.9; 6 V

K.2 Sensitivity

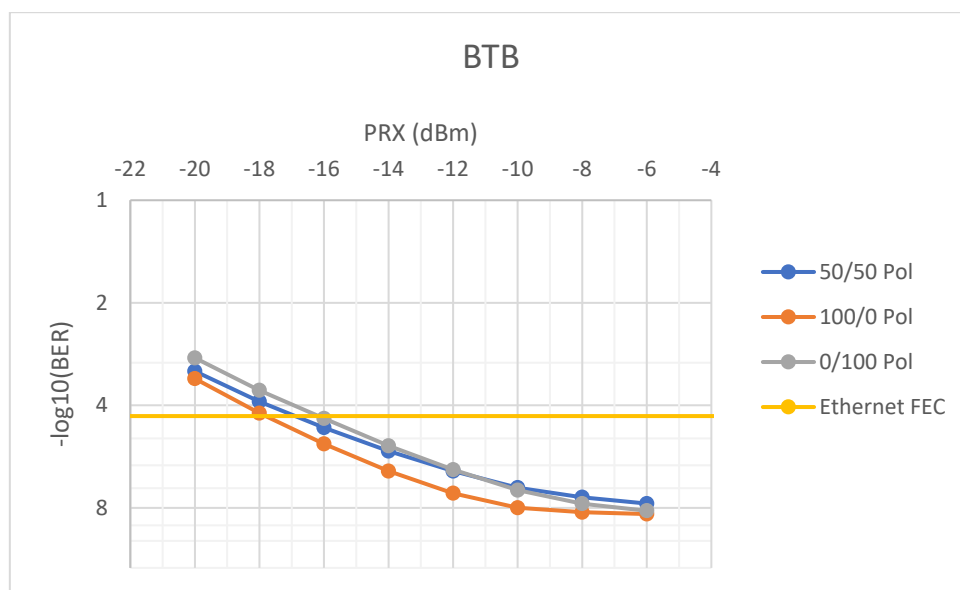


Figure 29. Sensitivity curve ROSA_QCR7A6609 for BTB with IF ±.99 GHz

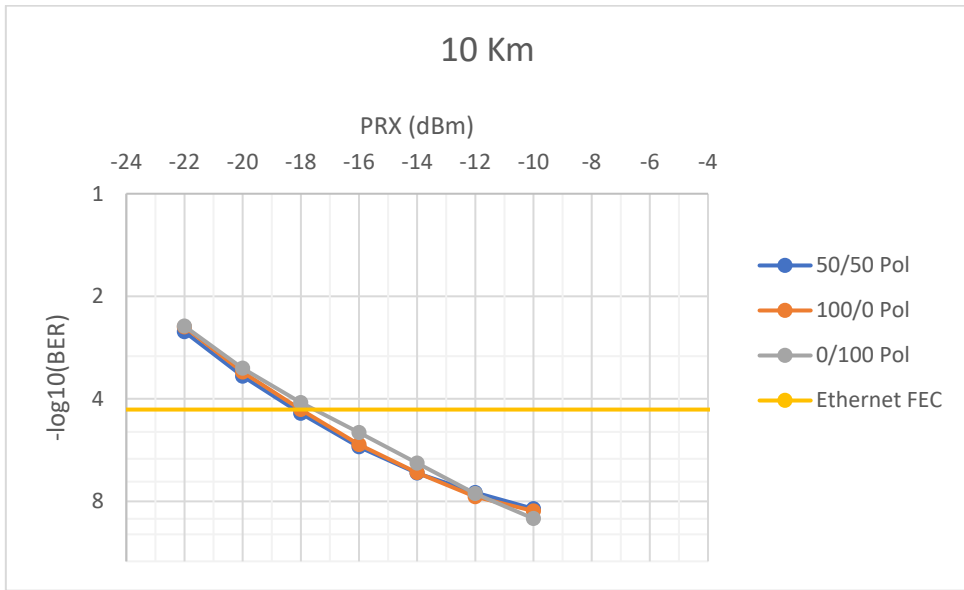


Figure.20 Sensitivity curve. ROSA_QCR7A6609. for.76.Km.with.IF.±.98.GHz

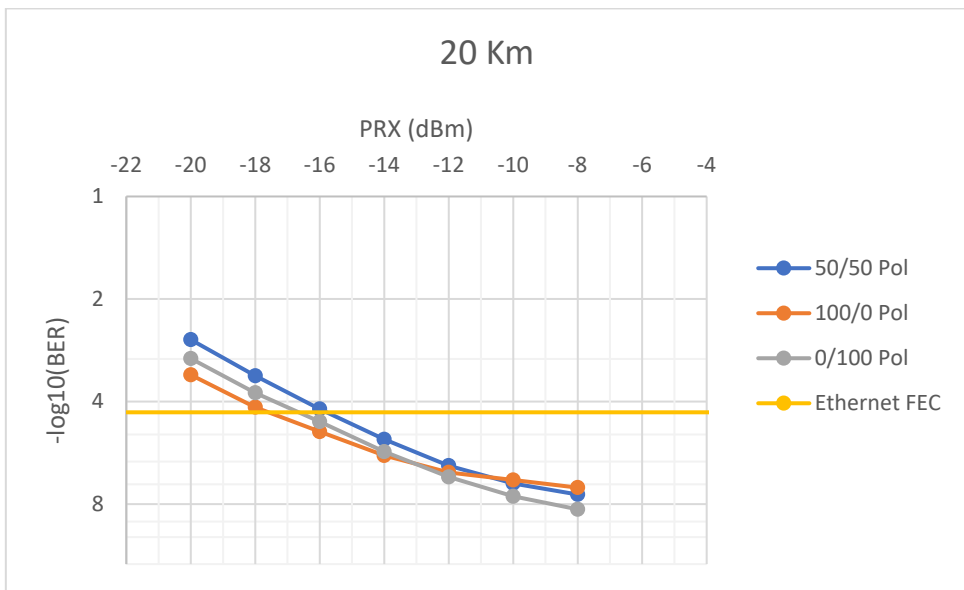


Figure.21 Sensitivity curve. ROSA_QCR7A6609. for.86.Km.with.IF.±.80.GHz

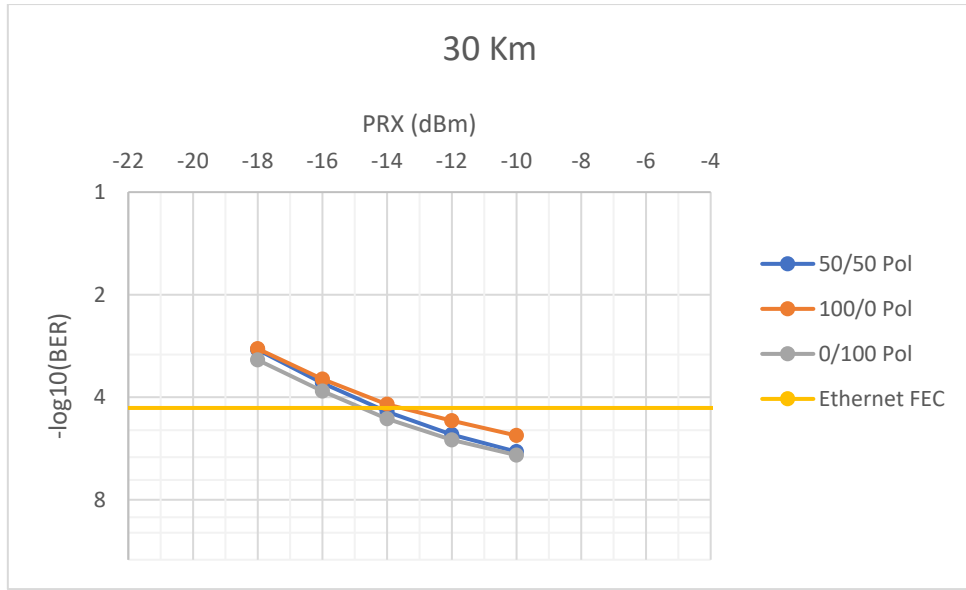


Figure 22 Sensitivity curve ROSA-QCR7A6609 for 96 Km with IF ± 99 GHz

L. Results of ROSA-QCR1A0044

L.1 Frequency sweep

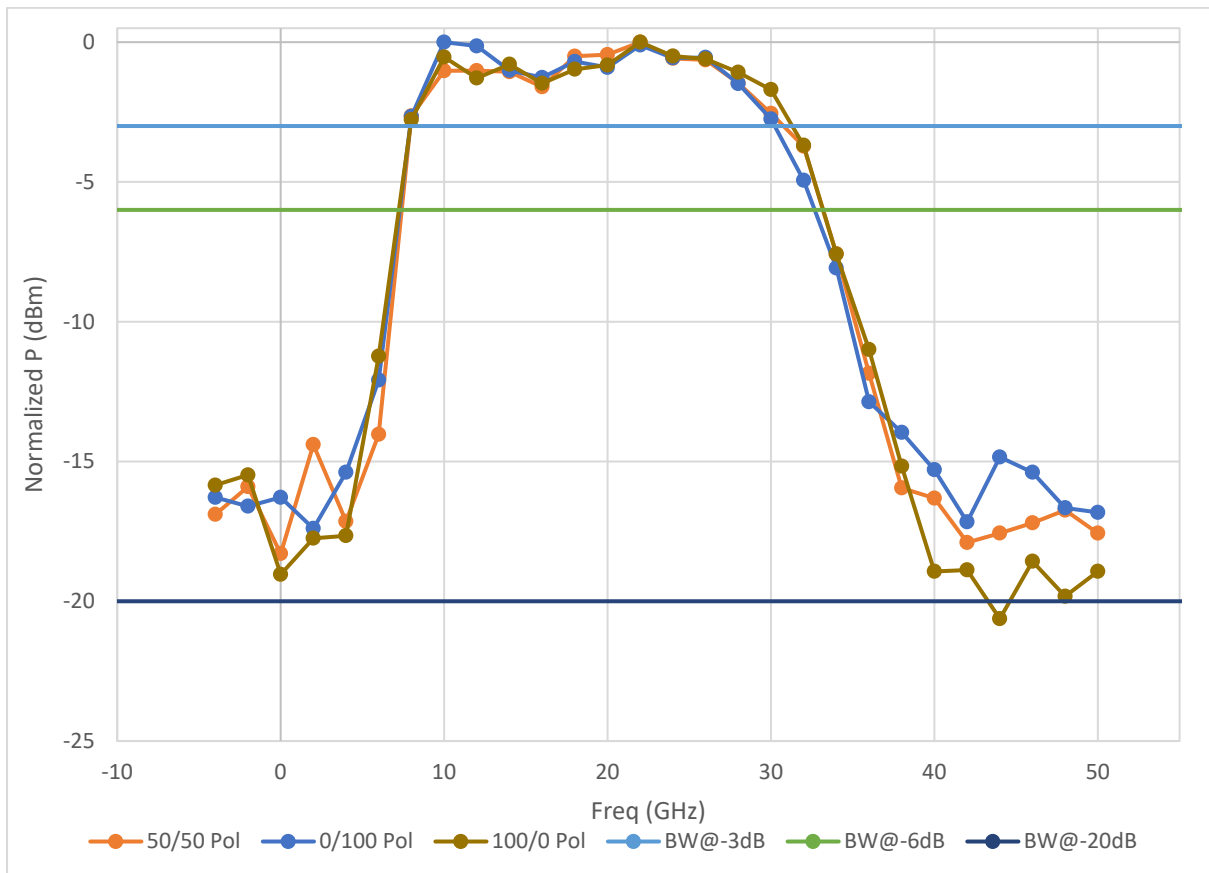


Figure 23 Frequency sweep for ROSA-QCR7A6600? Signal power ± 86 dBm? gain ± 9; 6

L.2 Sensitivity

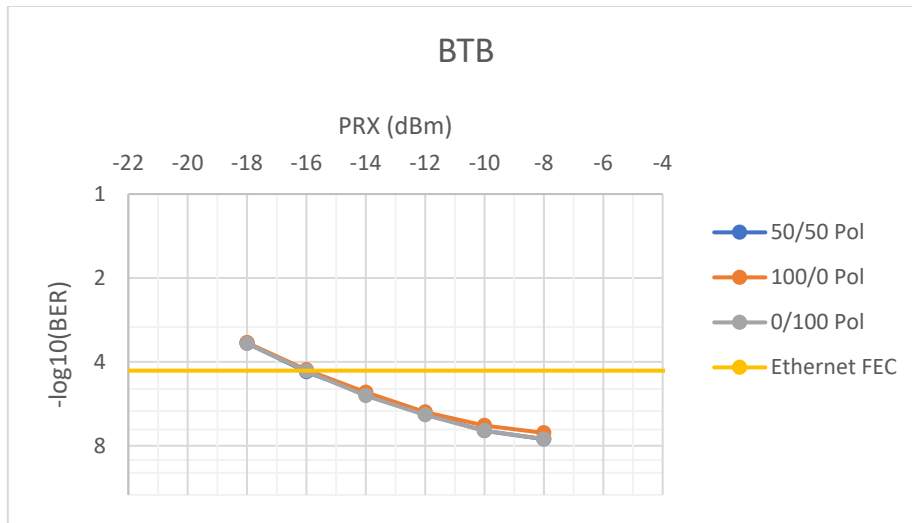


Figure 24 Sensitivity curve ROSA_QCR7A6600 for BTB with IF ± 97 GHz



Figure 25 Sensitivity curve ROSA_QCR7A600 for 76 Km with IF ± 96 GHz

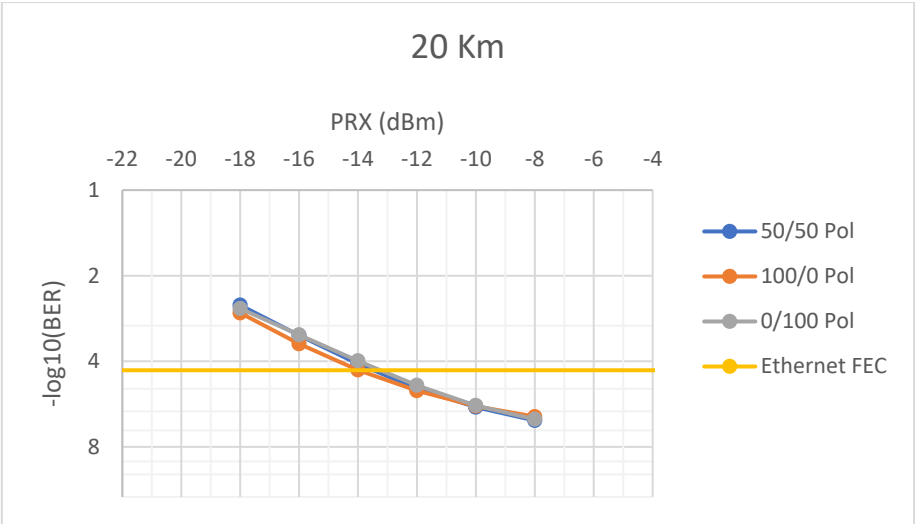


Figure 66. Sensitivity curve ROSA_QCR7A6600 for 86 Km with IF ± 80 GHz



Figure 67. Sensitivity curve ROSA_QCR7A6600 for 96 Km with IF ± 96 GHz

M. Results of ROSA-QCR1A0046

M.1 Frequency sweep

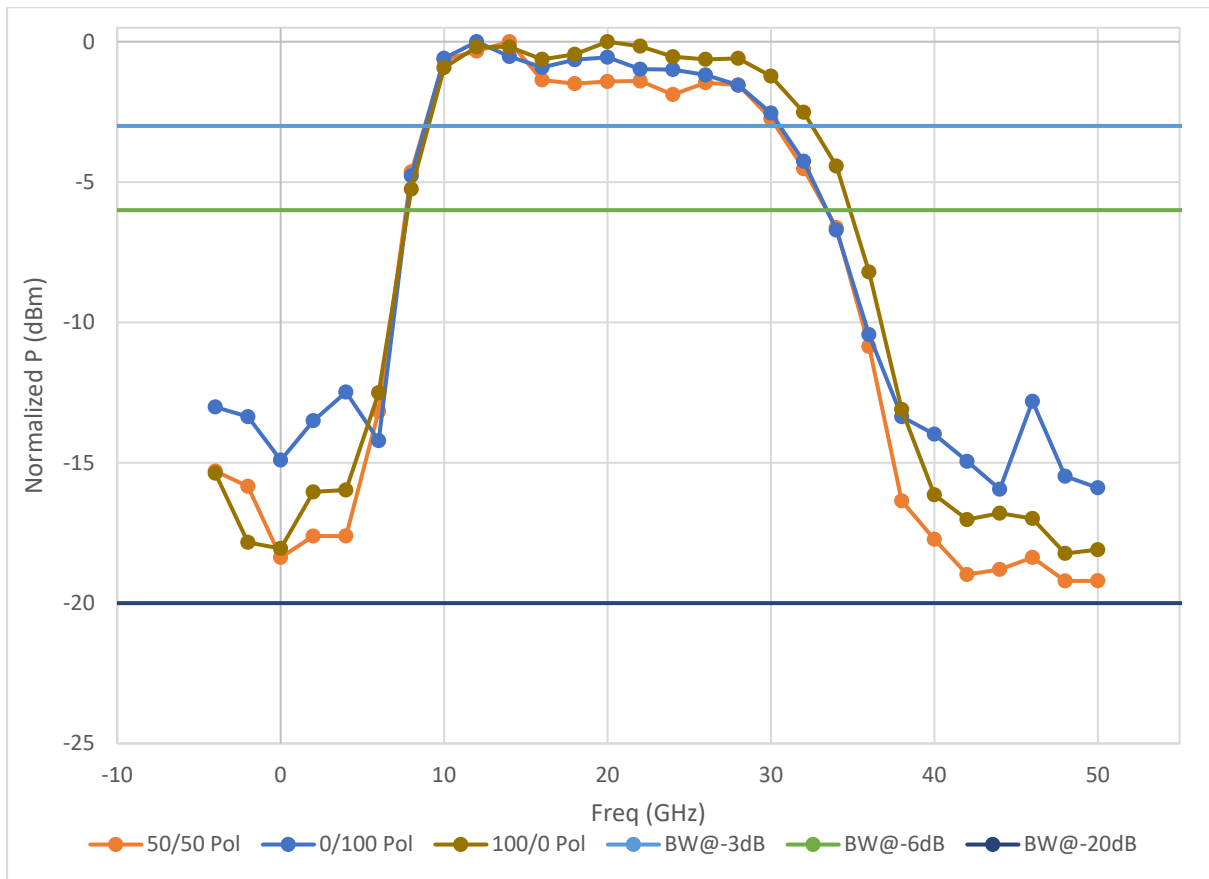


Figure 68. Frequency Sweep for ROSA_QCR7A66002. Signal power: ±.86 dBm? gain: ±.9162V

M.2 Sensitivity

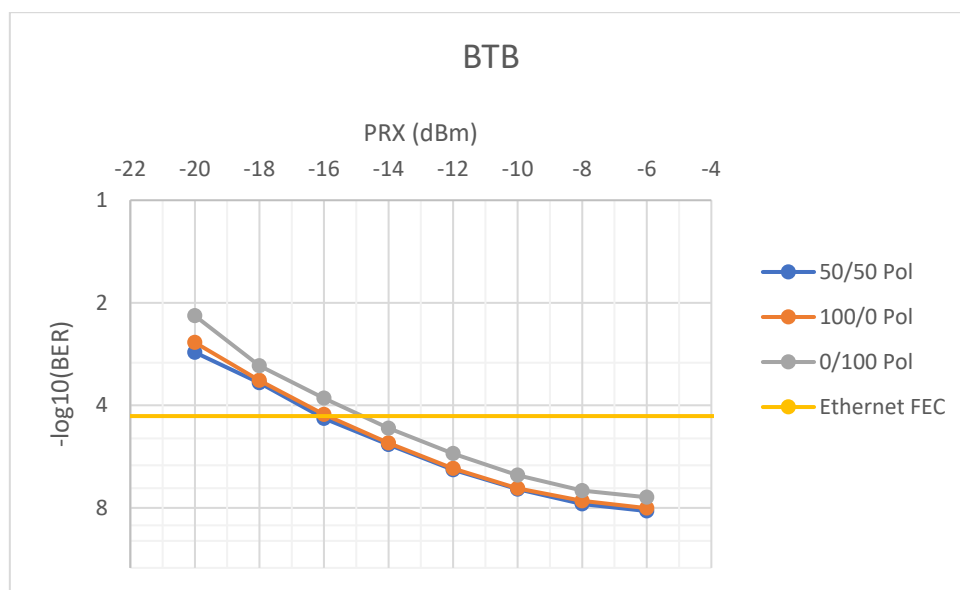


Figure 69. Sensitivity curve ROSA_QCR7A66002 for BTB with IF: ±.86 GHz



Figure 30 Sensitivity curve ROSA_QCR7A6602 for 76 Km with IF ± 8 GHz



Figure 31 Sensitivity curve ROSA_QCR7A6602 for 86 Km with IF ± 8 GHz

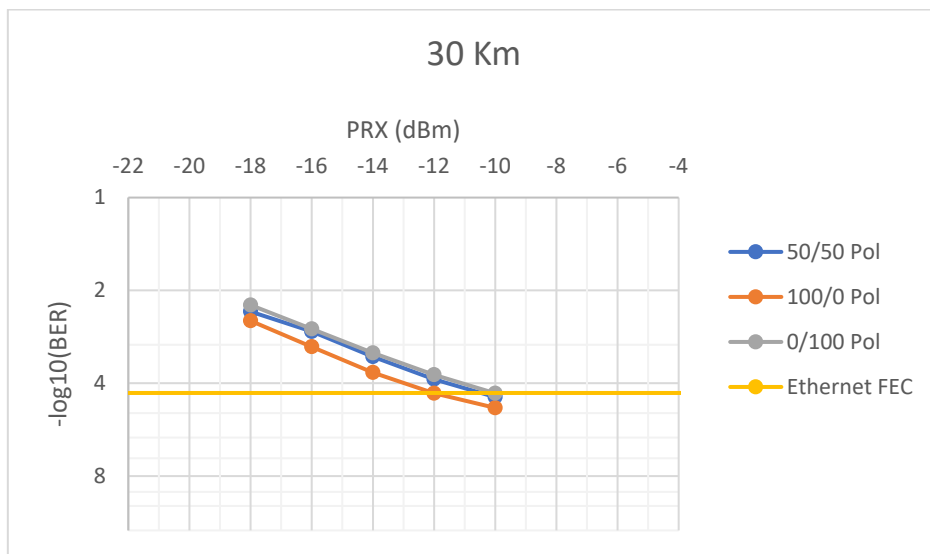


Figure 32 Sensitivity curve ROSA_QCR7A6602 for 96 Km with IF ± 9.7 GHz

N. Results of ROSA-QCR1A0047

N.1 Frequency sweep

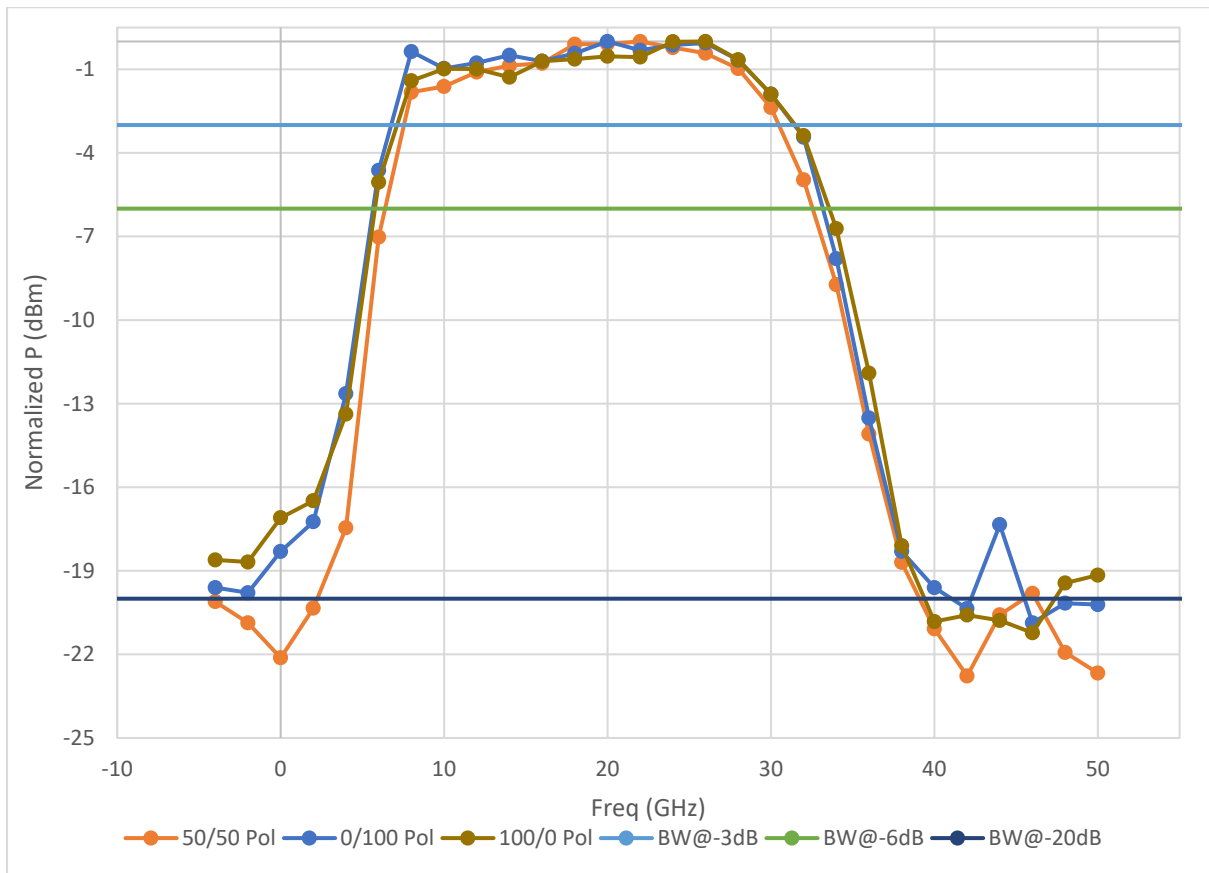


Figure. 63 Frequency sweep for ROSA_QCR7A6600 for Signal power \pm .86 dBm gain \pm .9j6 V

N.2 Sensitivity

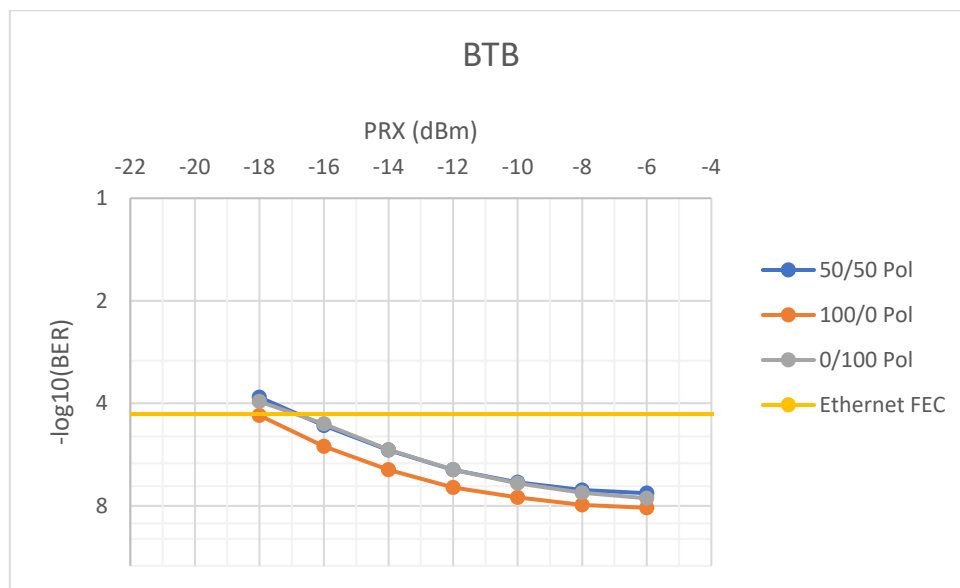


Figure. 64 Sensitivity curve ROSA_QCR7A6600 for BTB with IF \pm .96 GHz

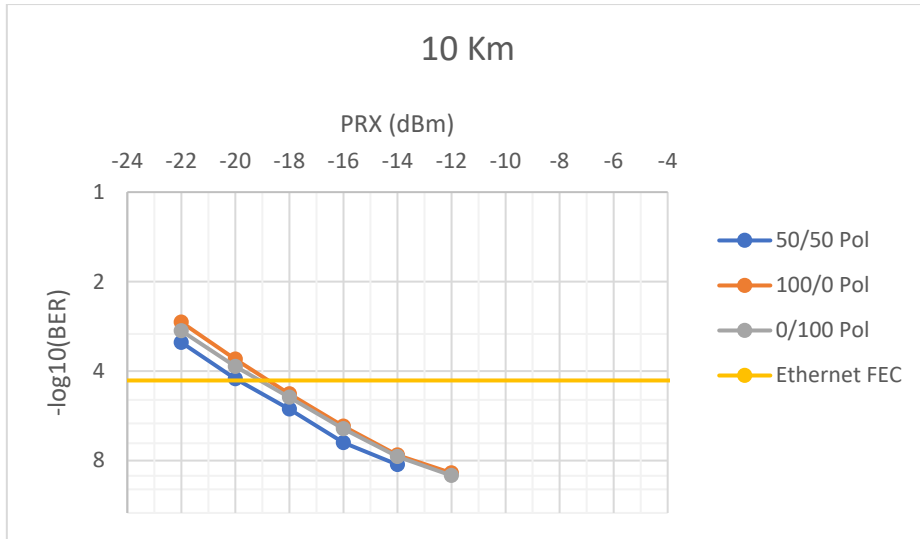


Figure.39.Sensitivity.curve.ROSA_QCR7A6600for.76.Km.with.IF.±.96.GHz

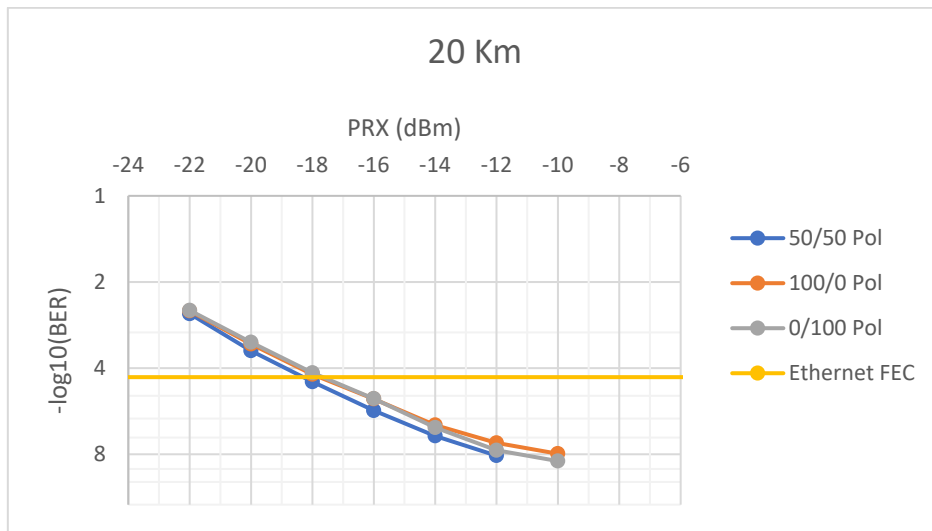


Figure.46.Sensitivity.curve.ROSA_QCR7A6600for.86.Km.with.IF.±.80.GHz

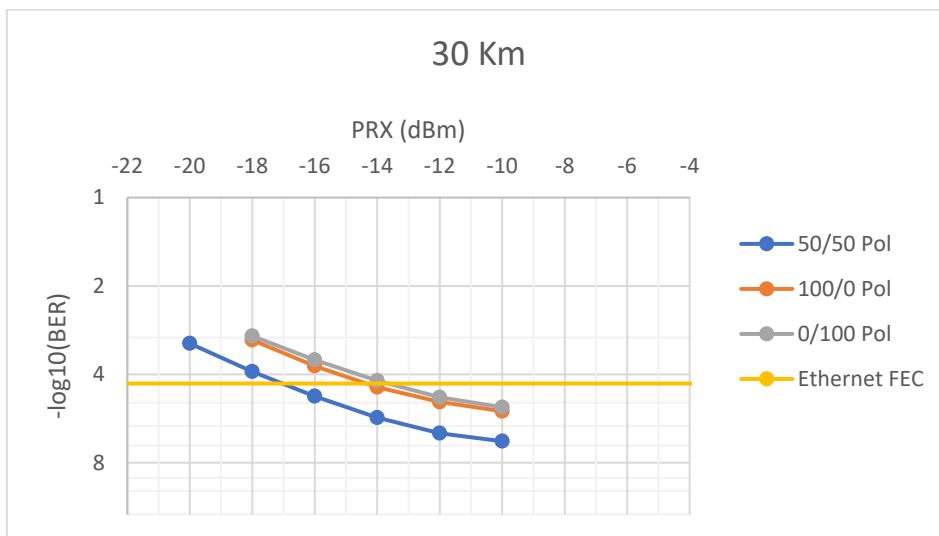


Figure.47.Sensitivity.curve.ROSA_QCR7A6600for.96.Km.with.IF.±.96.GHz



Appendix 6

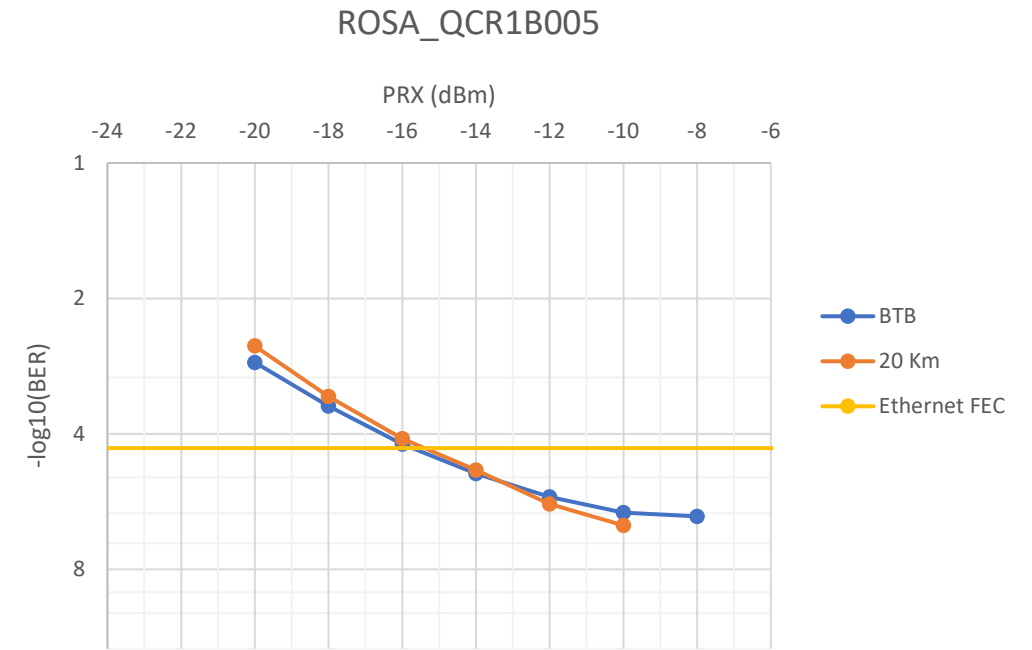
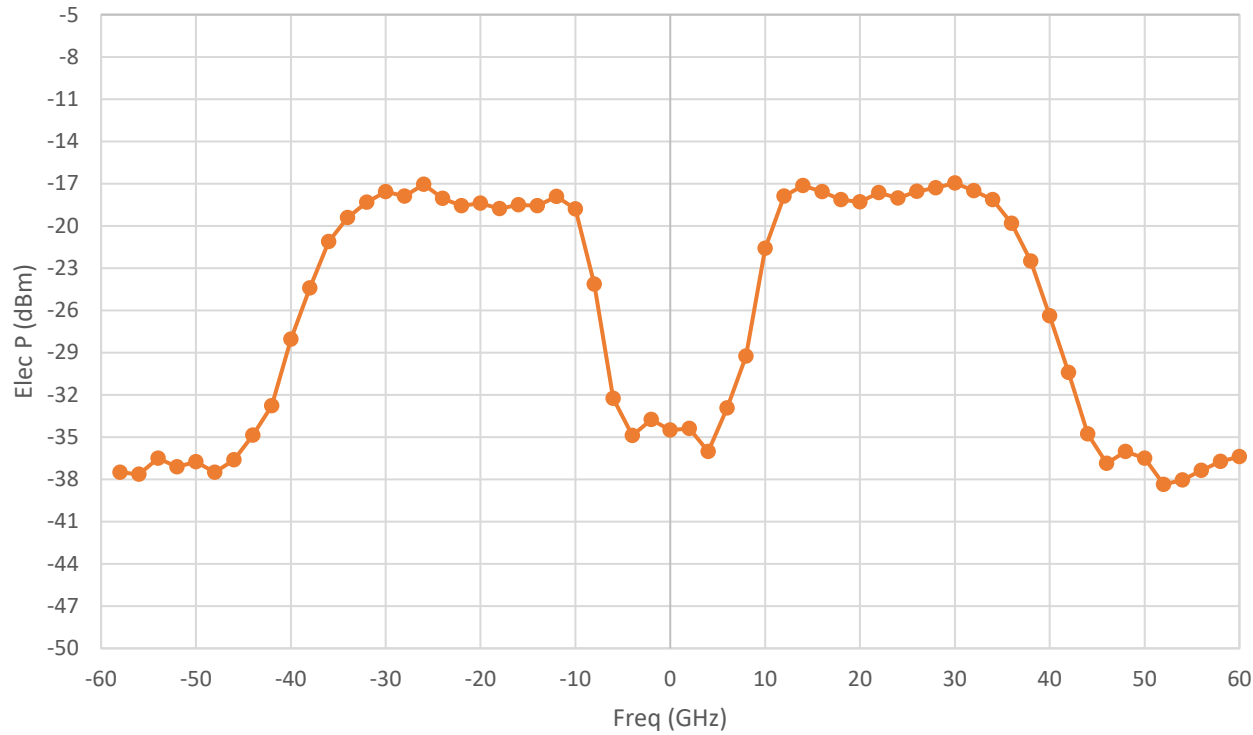
AVO Bulk ROSA with First Opto Housing

AVO bulk ROSA tests

This Appendix collects the tests of the two AVO bulk-optics QC-ROSAs with First Opto housings. The configuration used in the tests are highlighted in the table below. All tests were performed at 25 Gbps.

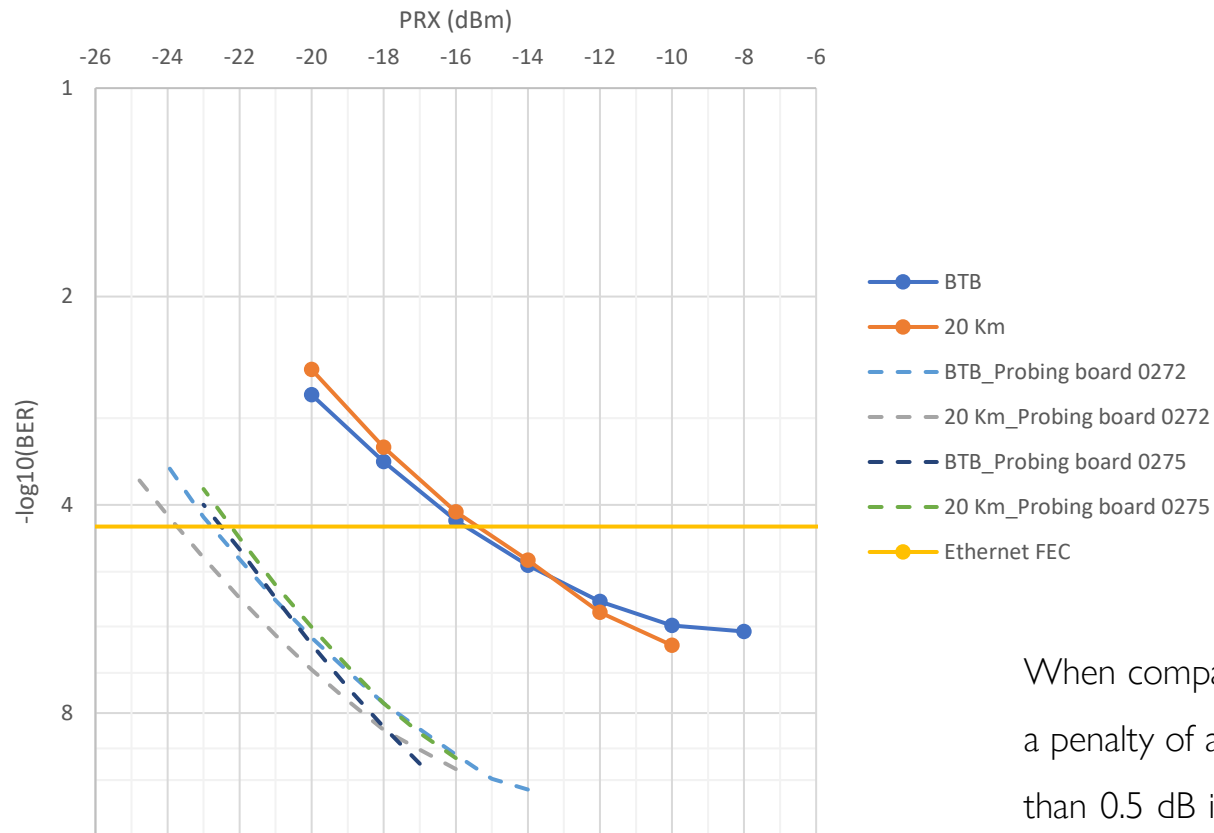
PD	Wooriro CPC5012S
TIA	CD25_063 (20 km reach)
ED	
TX	ATOP with Keysight N4980A PPG
CDR	Semtech GN2146 eval board

Frequency sweep and sensitivity results



ROSA	ASIC	BW @-6dB (GHz)	Excess Insertion Loss (dB)				Sensitivity – BTB (dBm)	Sensitivity – 20 Km (dBm)
			LO (EL1) Left	LO (EL 2) Right	Signal (EL 1) Left	Signal (EL2) Right		
QCR1B004	063	Unable to Control TEC		3	2.81	Unable to control TEC		
QCR1B005	063	28	0.2488	0.3862	3.294	1.705	-15.7	-15.3

Bulk ROSA Receiver sensitivity measurements



ROSA / Probing board	ASIC	Sensitivity – BTB (dBm)	Sensitivity – 20 Km (dBm)
ROSA_QCR1B005	063	-15.7	-15.3
Probing board_0272	063	-22.8	-23.7
Probing board_0275	063	-22.5	-22.2

When comparing ROSA_QCR1B005 with the evaluation boards using the same PD and ASIC, it has a penalty of around 6 dB in the sensitivity. This can partly be explained by an excess insertion loss less than 0.5 dB in the LO paths and more than 1.5 dB in the signal paths with one of the paths having around 3 dB loss. The remaining 4 dB penalty is attributed to non-optimal beam wavefront overlap at the PD surface between signal and LO. This highlights the advantage of moving towards a PIC implementation where perfect wavefront overlap is secured by the PIC waveguides



Appendix 7

AVO Bulk ROSAs with Kyocera Housing

Description

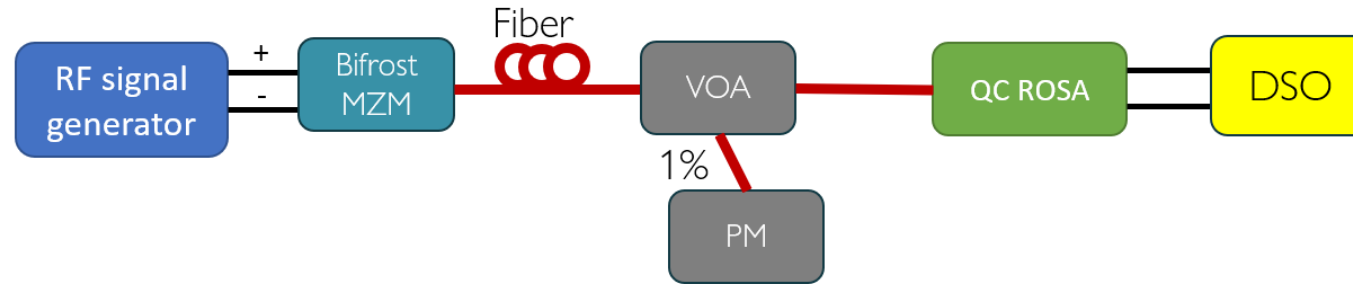
Test Results of 6 units of Bulk ROSAs received from AVO

Housing	Kyocera
PD	CPC5012S
TIA	CD25_068
ED	
TX	ATOP with Keysight N4980A PPG
CDR	Semtech GN2146

Measurement of Excess loss

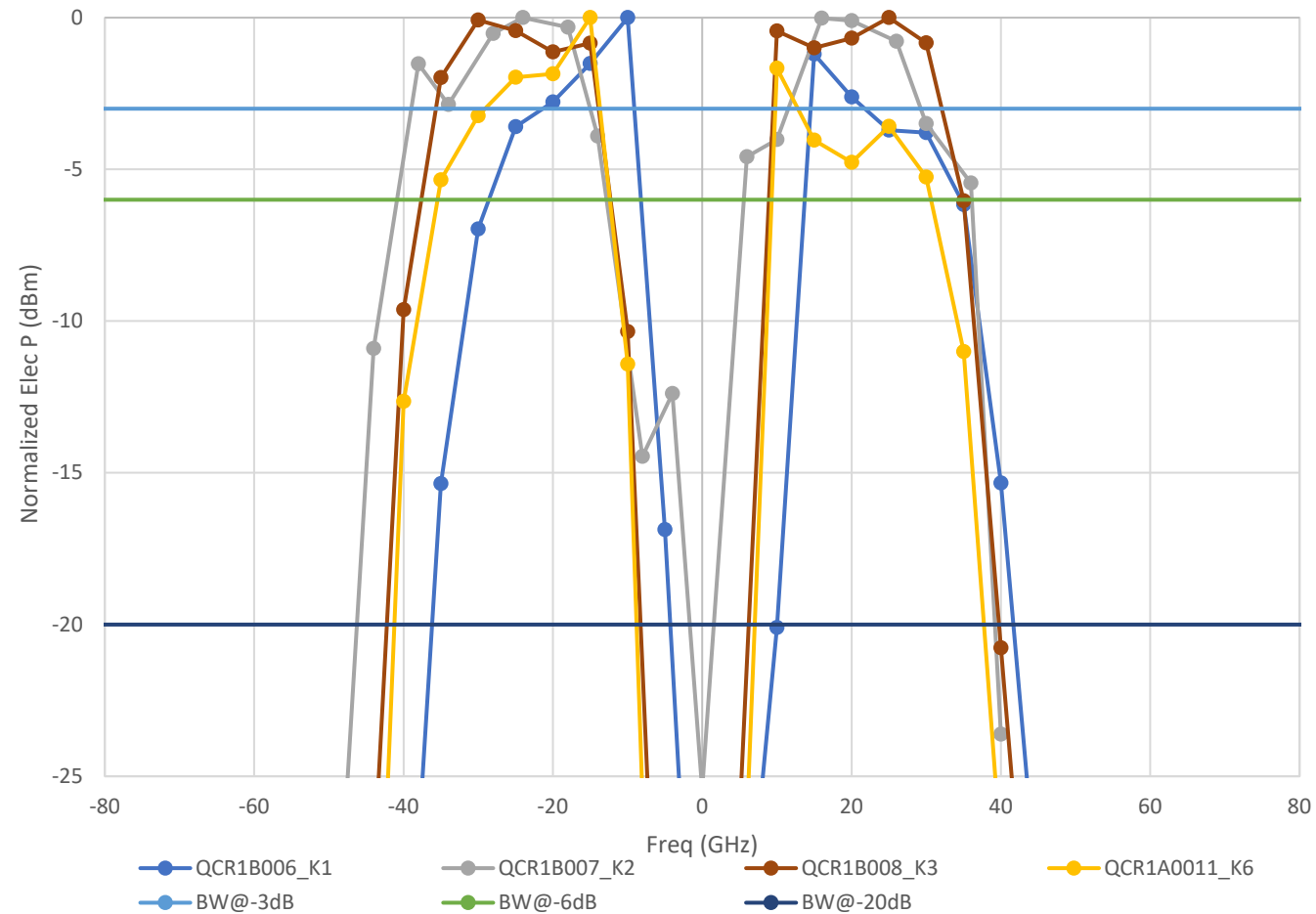
The theoretical insertion losses for the ROSA are 7 dB for LO to the PD (3 dB from the PBS and 4 dB from the asymmetric coupler), and 5.2 dB from the input receptacle to the PD (3 dB from the PBS and 2.2 dB from the asymmetrical coupler). Any extra losses that are presented higher than the theoretical insertion loss is referred to as excess loss. For measuring the excess loss, RSSI values are noted down when the signal and LO are turned on separately, and the insertion losses for LO to PDs and signal to PDs are calculated. Finally, the excess loss is calculated by subtracting the measured insertion loss from the theoretical insertion loss.

Setup for performing frequency sweep



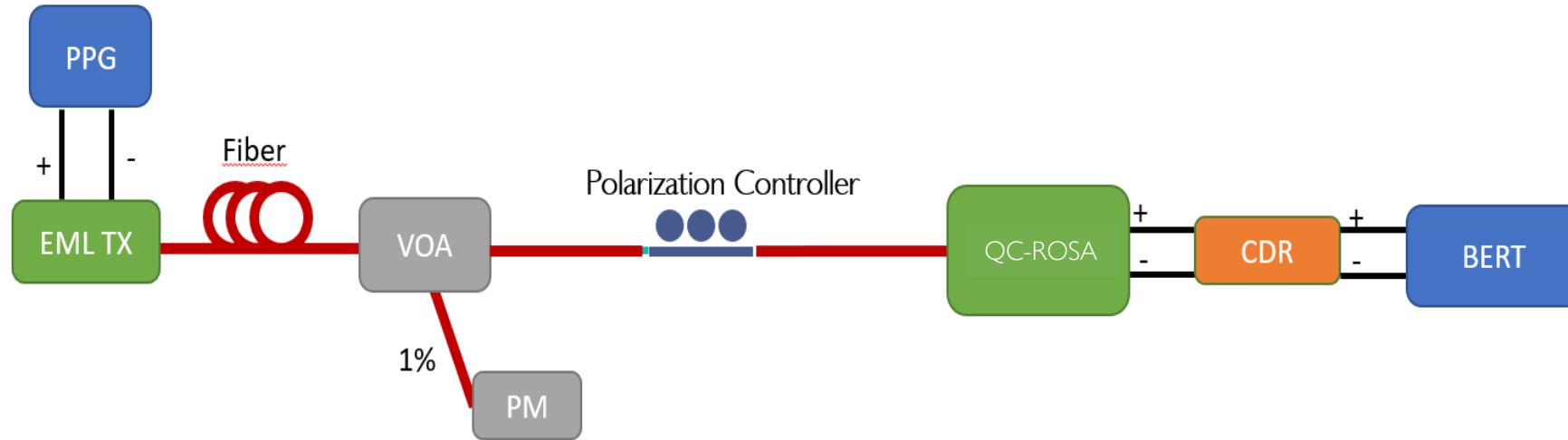
The setup consists of a Bifrost MZM driven by 1 GHz RF signal generator. The signal is then transmitted through a single mode fiber (usually in the BTB mode) to the QC-ROSA. Simultaneously the LO is activated at a specific wavelength such that it matches with the signal wavelength. One of the output of the ROSA is connected by a load capacitor and the other is connected to a DSO which acquires the signal in real time. The whole system is controlled by a program externally which then sweeps over a range of intermediate frequencies at a specific power and gain setting to acquire the frequency spectrum of the ROSA.

Frequency Sweep



- The frequency sweep allows to characterize the combined input bandwidth of the ROSA. An ideal estimate would be to measure the bandwidth at -6dB.
- The -6dB bandwidth for the units are around the range of 25 GHz to 30 GHz. This provides enough room in terms of the operating bandwidth.
- The frequency sweep curve for the unit QCR1B006_K1 appears to be shifted in terms of the frequency range, this could be attributed to the previously mentioned issue with the polarization alignment.

Setup for measuring sensitivity



The setup consists of an EML transmitter (ATOP) driven by a PPG (Keysight). The signal is then transmitted through a standard single mode fiber of the desired distance before it reaches the ROSA. The two RF output channels of the ROSA are connected to a CDR (Semtech) which in turn is connected to a BER test setup. The data rate used here is 25 Gbps and the sensitivity is measured over different distances of fiber.

Summary of Results

ROSA	ASIC	BW @-6dB (GHz)	Excess Insertion Loss (dB)				Sensitivity BTB (dBm) [Best case]	Sensitivity 20 Km (dBm) [Best case]	Sensitivity 40 Km (dBm) [Best case]	
			LO Left	LO Right	Signal Left	Signal Right				
QCR1B006_K1	068	25	0.265	0.417	7.511	1.353	Unable to measure			
QCR1B007_K2	068	30	0.076	0.108	1.983	2.002	-10	-12	Unable to measure	
QCR1B008_K3	068	28	0.680	0.604	1.249	2.382	-10	-16	-12	
QCR1B009_K4	068	Broken								
QCR1B0010_K5	068	Unable to test	0.032	0.823	0.924	0.667	ROSA lid opened, unable to test			
QCR1B0011_K6	068	25	0.612	0.818	3.787	3.845	-10	-16	-12	

- The module QCR1B006_K1 exhibited an issue related to polarization alignment, wherein the RSSI values of both channels varied in the same direction, either increasing or decreasing simultaneously. Under ideal conditions, proper polarization alignment to one channel should result in a corresponding reduction of the RSSI in the other channel. This might explain the high insertion loss in one arm and the inability to measure sensitivity.
- The lid of the ROSA for QCR1B0010_K5 had opened while soldering the flex with the PCB, therefore it was unable to get any RF output from that unit.

Conclusion

- The performance of latest build with Kyocera housings were below acceptable levels, with two modules damaged out of the six. In the remaining four one seemed to have a misalignment in the design especially with the polarization; therefore, it was unable to perform a complete characterization in that module.
- The insertion losses and the frequency sweep Was within requirement specifications for the other 3 modules, however the sensitivity for these modules were from -10 dBm to -16 dBm over different fiber distances – 0Km, 20 Km and 40 Km. This is 6-8 dB worse than expected from eval board measurements using the same ASIC and PD, and can therefore not solely be explained by the ROSA excess insertion loss. We are in dialog with AVO to investigate this further
- Overall conclusion is that moving towards PIC modules over bulk ROSAs is a better option. Despite this conclusion, the bulk ROSA development project gave us valuable insight and experience into photonic packaging, which have helped accelerate the PIC-ROSA and SFP projects



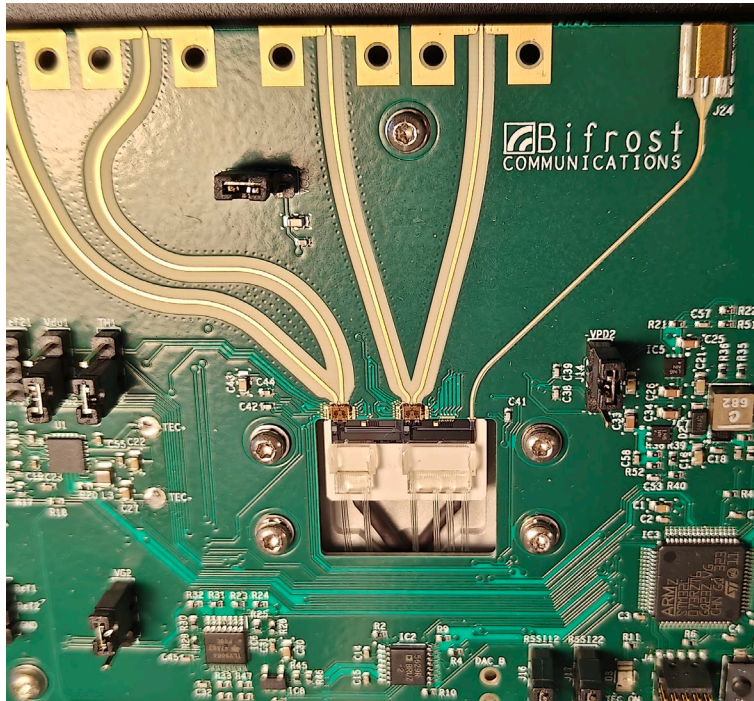
Appendix 8 From PIC Test Board to SFP

Introduction

This Appendix goes through the various development steps in the PIC-ROSA packaging and SFP implementation. It starts with a description of our PIC test board platform and concludes with a successful test of the final SFP transceiver.

All development have been carried out in-house at Bifrost Communications in close collaboration with Sanmina for the PIC test board, AVO Photonics for the ROSA, and Estel for the QSFP and SFP.

The capability of us at Bifrost to address all parts of this development, from high-speed ASIC and PIC design, over optical incoupling and RF signal integrity to thermal, mechatronics, control and DC implementation is a major result of the EUDP project.

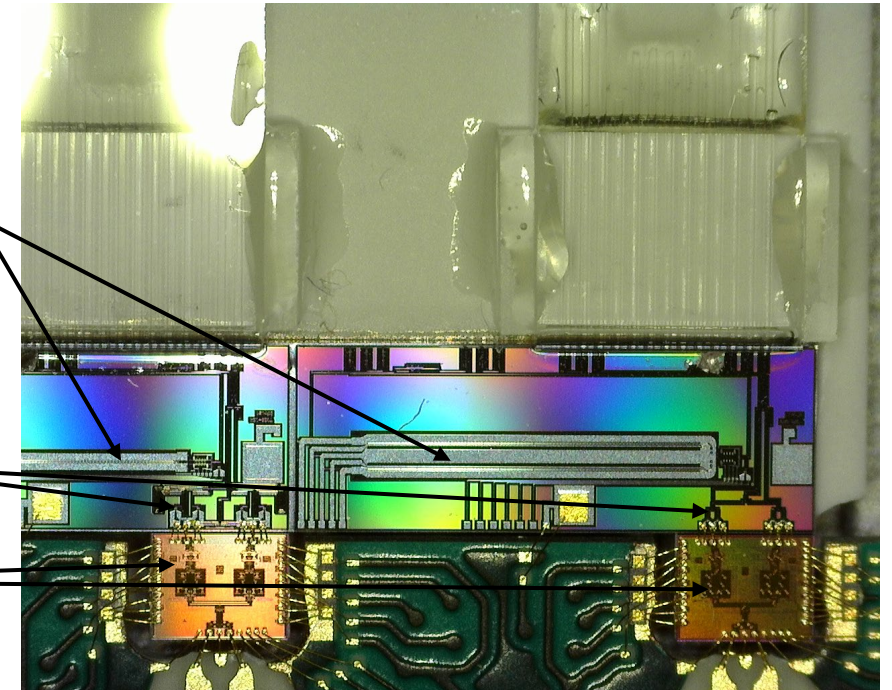


PIC Test-board

Optical Modulators for TX

QC-Receiver Optics

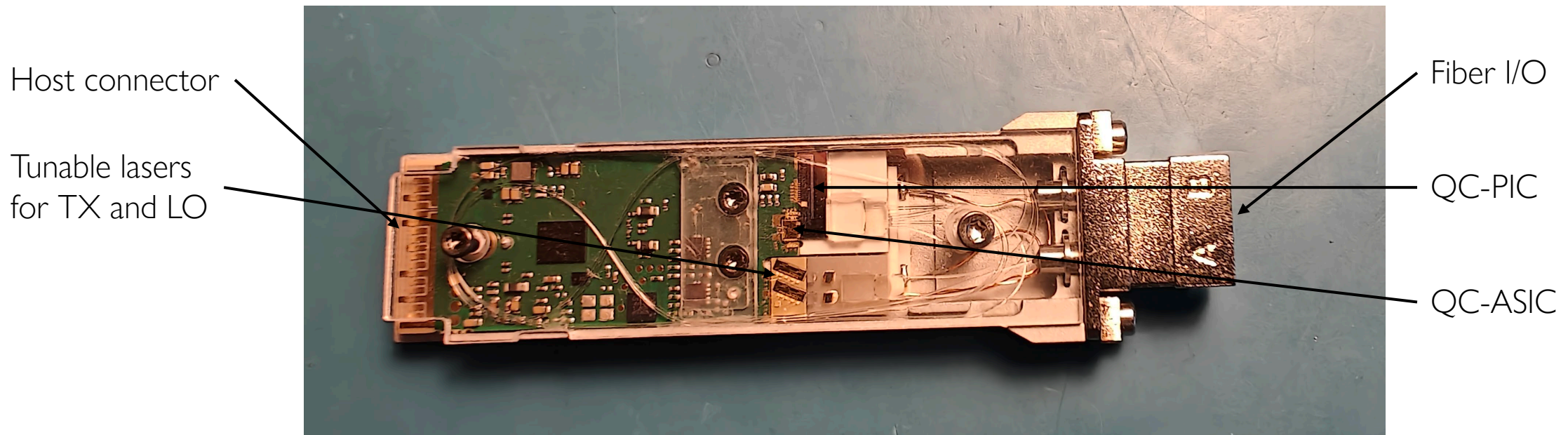
QC-ASICs



The picture on the left shows our first test platform for the PIC-ROSA components. It contains 2 transmitter and receiver variations on each PIC. The receiver PICs are wirebonded to QC-ASICs. This platform allows us to test various PIC and ASIC combinations. Signal and LO light is coupled to the PIC with a fiber harness.

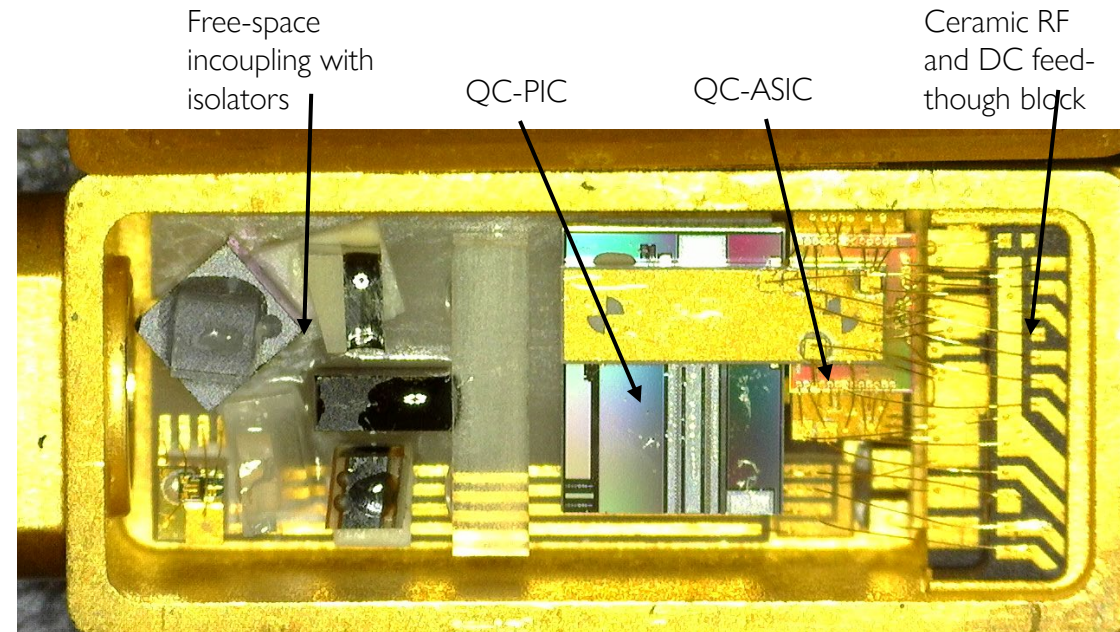
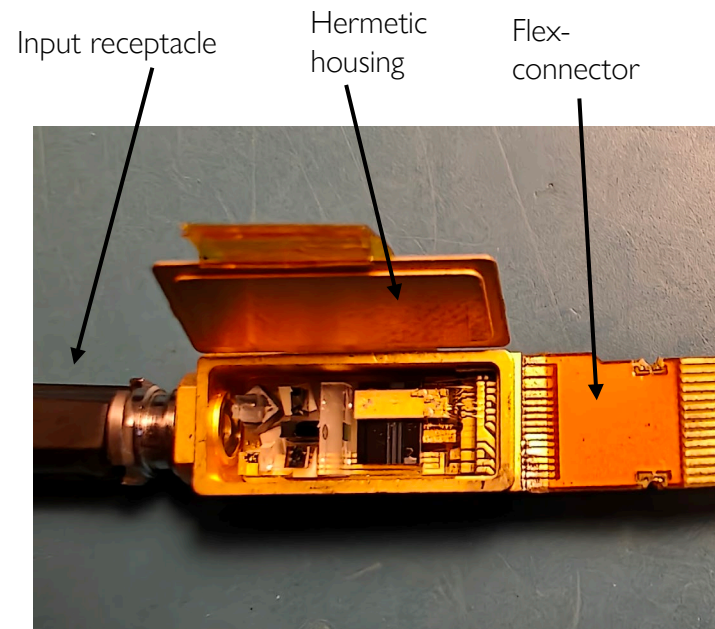
The picture on the right shows a microscope image of the central part with the PIC, ASICs and fiber harness

QSFP Prototype



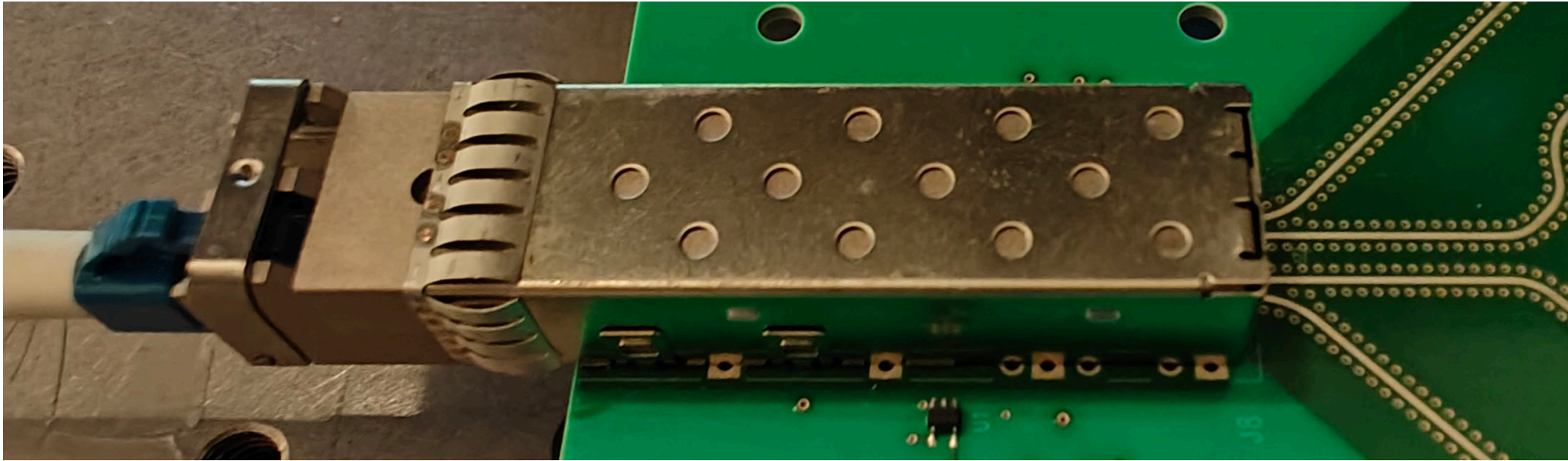
The test board on the previous slide was designed to facilitate easy transition to a QSFP prototype. This is shown in the picture above. This is the QSFP that was used for customer demonstrations at the OFC conference April 2025. It uses tunable lasers for TX and LO, and is thus a tunable transceiver prototype. Due to the open (non-hermetic) mounting platform, this implementation cannot be qualified for I-temp (-40 to +85 degrees C) operation.

PIC-ROSA



In parallel with the QSFP prototype development, we developed a hermetically sealed PIC-QC-ROSA that would comply with requirements for I-temp operation. This version is a non-tunable version, which allows for the use of off-the-shelf transmitter EML TOSA in order to reduce cost, complexity and power consumption of our first pluggable transceiver commercial offering. The PIC-QC-ROSA is shown on the left with a microscope image showing details on the right. Due to the size constraints and hermiticity requirement, a free-space optical incoupling scheme incorporating optical isolators had to be developed.

SFP Transceiver



The PIC-QC-ROSA has been integrated into our first SFP transmitter together with an off-the-shelf EML transmitter. Clock and data recovery is performed by a standard chip provided by Semtech, which is the market leader in this space. The SFP mechatronic and firmware have been developed in close collaboration with Estel, who will be the volume manufacturer of the SFP.

SFP test and conclusion



The SFP have been tested by the CM Estel. The picture shows a screen-shot of a 45 minutes test where more than 30 billion frames of data was transmitted at 25 Gbps over 40 km of standard single mode fiber without a single errored or dropped frame. At room temperature, the SFP power consumption is only 1 W - well below the 3W target.

This result shows that the PIC, ROSA and SFP development have been highly successful. It has brought us to a point where we are not only able to offer QC-ROSA to existing transceiver vendors for them to integrate into their own SFP. We are now able to offer a complete transceiver solution directly to the end customer.

We have demonstrated this to customers, including Nokia and Ericsson, at the European Conference on Optical Communication (ECOC) 2025 in Copenhagen.

PIC ROSA and SFP Preliminary tests

The test reported in the following pages are still ongoing and are therefore to be considered preliminary

Introduction

	Description
PD	CPC5012S
TIA	CD25_072
ED	
TX	Almae & ATOP with Keysight N4980A PPG
CDR	Semtech GN2146

- Preliminary measurements were done with SFP28_SN0003.
- These tests were done with both Bifrost SFP (with Almae laser) as the TX and ATOP SFP as the TX in order to provide a fair comparison against the performance of a standard commercial transceiver.
- The RSSI's for this unit were not working, as in the value was the same (2.5 V) irrespective of signal/LO being present or not. Therefore, it was unable to evaluate the excess insertion losses for this unit.
- All the measurements were carried out only for one (working) polarization, as there was no measurable BER in the other. Since the RSSI readings were not operational, it was not possible to determine which polarization the was signal aligned to. Further investigation is required to address the polarization issue.

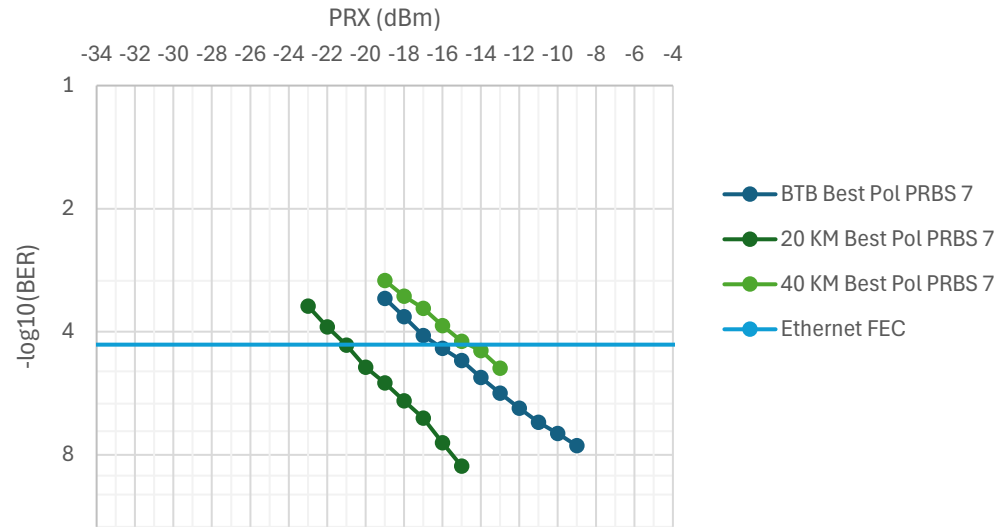
Insertion Loss AVO PIC - ROSAs

ROSA	IL (dB) - Signal (6 dBm)	IL (dB) - LO (9.5 dBm)
SN002 (SFP mounted)	11.18	5.27
SN003 (SFP mounted)	7.92	4.61
SN006	3.6	5.2
SN007	5.5	0.9
SN008	3.4	1.6
SN009	4	1.9

The measured insertion loss of the first 6 PIC-ROSA prototypes show that the CM AVO has gained experience in the mounting and alignment during the assembly of the first 2-3 units. After that, insertion loss seems to stabilize around 3-4 dB for the LO and 1-2 dB for the signal. These values are within the requirement specifications and indicate a robust design with potential for high yield.

Sensitivity

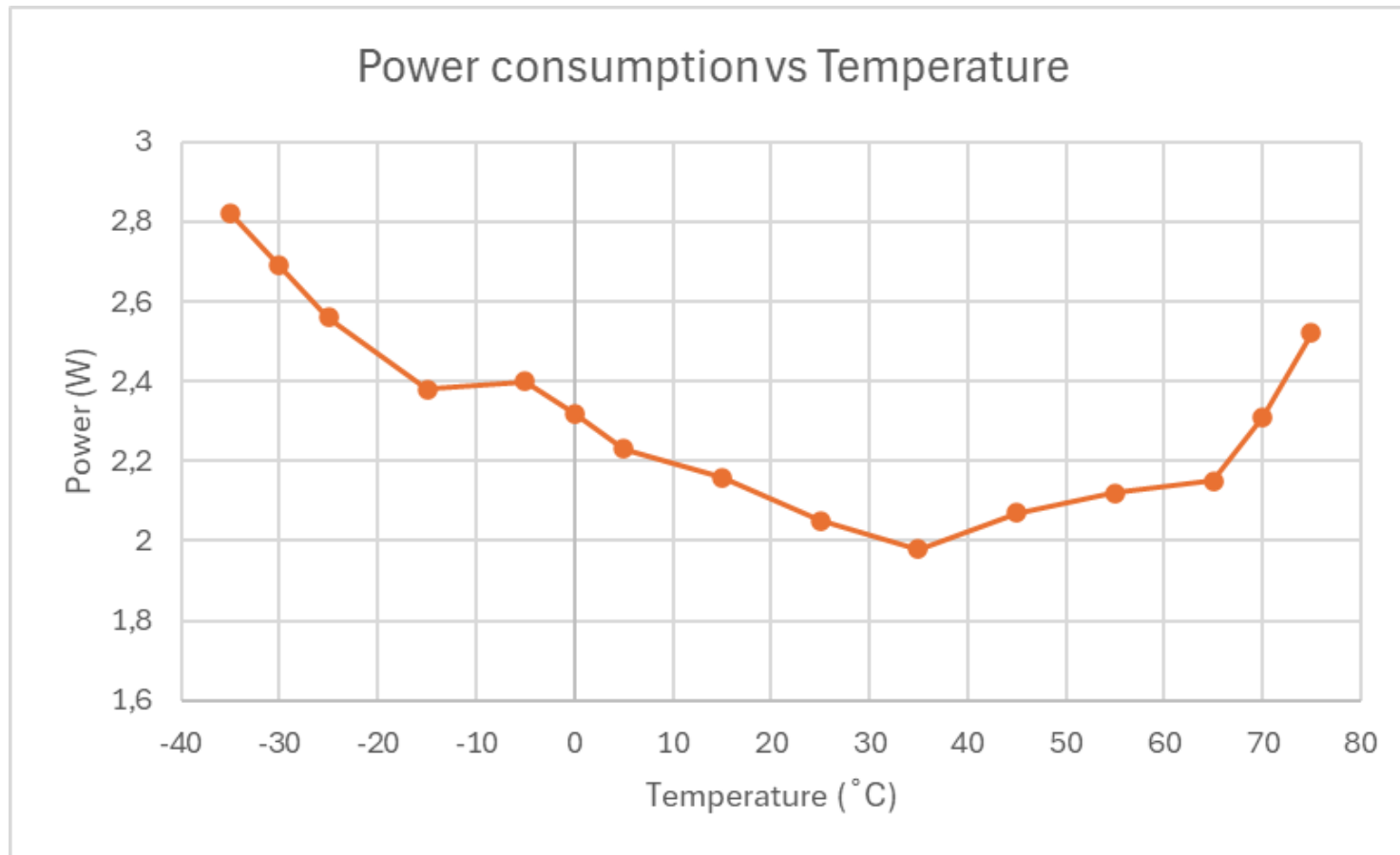
SFP 28 BFC TX-RX



Distance	Sensitivity (Almae TX)
BTB	-16.2 dBm
20 Km	-21 dBm
40 Km	-15 dBm

The tested SFPs have demonstrated excellent performance when transmitting from one unit to the other. This is particularly impressive considering that these SFPs use the first 2 PIC ROSAs, which have high insertion loss and high polarization dependence in the optical coupling. We expect to improve sensitivity over all by 3-5 dB when we start testing the next units.

Power consumption vs temperature for SFP unit



The power consumption vs temperature for the complete SFP was measured in the range -35 to +75 degrees. It remained below the 3W target for the entire range. We still need to conduct more measurements at -40 and +85 degrees, but these initial results are very promising

Conclusion

- The development from our first PIC to a final SFP prototype has been highly successful, and is a direct result of the EUDP project and all the experience gained within the development and tests of the Bulk ROSAs.
- The first PIC-ROSA prototypes have been mounted in SFP transceivers, tested, and demonstrated to customers at the European Conference on Optical Communication (ECOC)
- 40 km transmission in the C-band was achieved with very good stability – the setup was running for hours on several days during the ECOC conference
- The contract manufacturer AVO have quickly gained experience in the alignment and assembly of the PIC-ROSAs. From the measurements of PIC-ROSA insertion loss, we can expect a 3-5 dB sensitivity improvements in the next SFP units that are currently being mounted.
- Initial power consumption vs temperature measurements indicate that the SFPs will be able to pass the demanding I-Temp requirement (-40 to +85 degrees), but also show that some tweaks in the temperature control firmware can bring further improvements in this respect
- An additional highlight is the SFPs are manufactured in Europe and not overseas – thereby strengthening Europe's independence in strategic areas such as telecom and datacom.