Unpreamplified Heterodyne Detection of 10 Gb/s NRZ-OOK with High Receiver Sensitivity

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ABSTRACT

We report -31 dBm receiver sensitivity for heterodyne detection of 10 Gb/s OOK without using an optical pre-amplifier. These are the highest receiver sensitivities for unpreamplified heterodyne 10 Gb/s detection. We also show the development of a coherent heterodyne balanced fiber optic receiver. The receiver incorporates a DFB or a solid state laser local oscillator, balanced PIN photodiodes, RF post amplifier, automatic frequency control (AFC), phase locked loop (PLL), polarization control, and precision power supplies in a small instrument case. We will show shot noise limited detection of amplitude modulated signals, cancellation of laser RIN noise, performance improvement using balanced detection at 2.5 and 10 Gb/s, and IF linewidth reduction.

Keywords: Coherent receiver, balanced photodiodes, automatic frequency control, phase locked loop.

1. INTRODUCTION

Recently there has been a renewed interest in coherent optical detection for the following reasons: a) coherent optical receivers achieve high receiver sensitivities; b) multilevel modulation formats can be detected very efficiently; c) optical WDM systems with high spectral efficiency can be implemented; and d) preservation of the optical phase allows electrical equalizers to efficiently compensate optical channel impairments. These advantages of coherent optical detection over direct detection can be used to overcome some of the obstacles that limit the data capacity and the reach of current direct detection systems, both fiber and free-space based. Most of the recent work on optical coherent receivers focused on homodyne detection with optical preamplification and a digital phase-locked loop (PLL). Experimental work was based on a 90° optical hybrid to detect the in-phase and quadrature component of the received optical signal and storing it with a high speed oscilloscope. The stored data is then processed off-line with a PC to demonstrate the functionality of a digital PLL. However, real time processing using a digital PLL implemented with fast field programmable gate array (FPGAs) has not yet been demonstrated.

Our work is focused on a heterodyne optical receiver without using optical preamplification. The proposed method will be compared with respect to other recent proposals for coherent optical detection. For example, the heterodyne detection requires a photodetector bandwidth of two to three times the data rate to accommodate the double sided data spectrum centered at the intermediate electrical frequency. The availability of Discovery Semiconductors' DSC740 40GHz balanced photodetectors makes 10Gb/s heterodyne detection feasible. For heterodyne detection, an analog implementation of the optical frequency locked loop is less challenging compared to the optical PLL required for homodyne detection. Avoiding the use of optical preamplifiers makes this coherent optical receiver useable for free-space applications at wavelength such as 1064nm [1]. A detailed experimental setup is described and the obtained measurement results are shown for unpreamplified receivers. Good receiver sensitivities of unpreamplified heterodyne receivers have been shown in the past for data rates up to 4Gb/s. We discuss sensitivity improvement for 2.5 and 10 Gb/s using balanced detection versus single-ended detection. In this paper, we show a high receiver sensitivity of -31dBm for 10Gb/s on/off-keying (OOK). To the best of our knowledge this is the highest sensitivity achieved for heterodyne 10Gb/s detection without using an EDFA as a preamplifier. We will discuss which parameters determine the receiver sensitivity.

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We demonstrate relative intensity noise (RIN) reduction using balanced detection to help explain the performance improvement over single-ended detection. Finally, we discuss the implementation of an automatic frequency control which allows for robust, field deloyability of the coherent receiver.

Sections 2 through 6 discuss the technical background, implementation and measurement results of Discovery's 1.55 µm optical coherent receiver system, and section 7 gives the concluding remarks.

2. BALANCED PHOTODETECTOR

Coherent optical communications systems employing balanced photodetection are vital for next-generation telecommunication links operating at 1.55 µm. These systems must operate with low power consumption and be of low weight. One of the core components in any high-performance balanced coherent receiver is the balanced photodetector. As explained in [2], the balanced photodetector must possess superior RF bandwidth matching in order to insure the required common-mode rejection ratio (CMRR) for high-sensitivity optical links. Fig. 1 shows the fiber-based 35 GHz balanced photodetector that Discovery uses in its 1.55 µm coherent receiver. Fig. 2 shows the excellent RF channel matching and CMRR of this device.

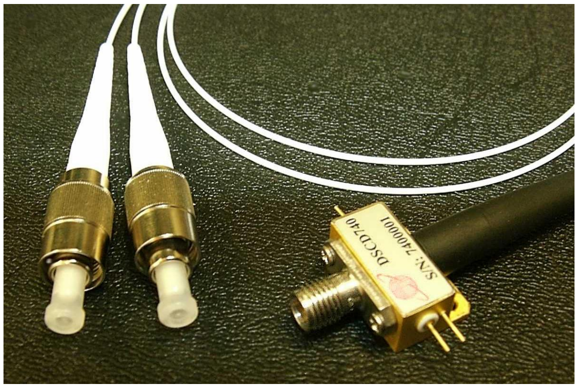


Fig. 1: Photograph of Discovery's 40 Gb/s balanced photodiode, Part Number DSC740, a critical component in its 1.55 µm coherent receiver system.

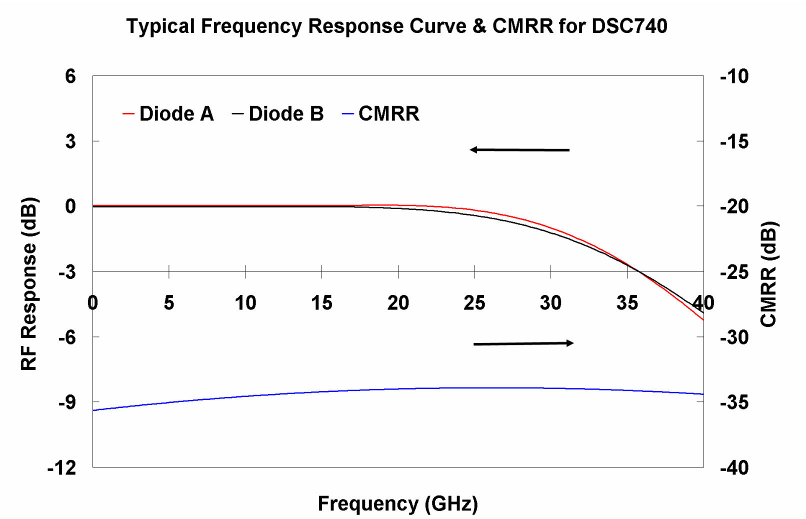


Fig. 2: RF response and CMRR of DSC740 balanced photodiode.

3. 1.55 µm COHERENT OPTICAL RECEIVER SYSTEM

Shown in fig. 3 is Discovery Semiconductor's bench top 1.55 µm optical coherent receiver system. This bench top model is designed for telecom, military and aerospace applications.

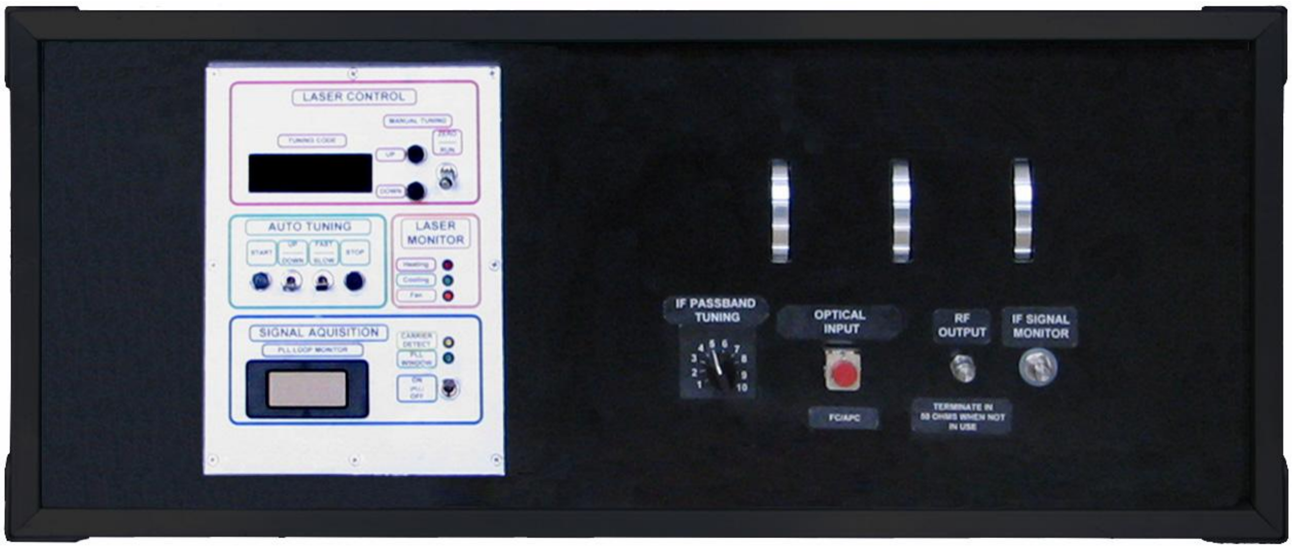


Fig. 3: Discovery Semiconductors' Coherent Optical Receiver "Kitty Hawk": The power consumption is only 108 W, thus, making it highly desirable as a payload on aerospace-based systems.

The performance of this receiver will be described throughout this paper. It has envelope dimensions of approximately 530 mm x 480 mm x 390 mm, and a total mass of 50 kg. The Discovery module can achieve data rates from 2.5 to 10 Gb/s. For 10 Gb/s operation it consumes 108 W.

The basic coherent receiver structure is shown in fig. 4 where the received optical signal is mixed with the light of an optical local oscillator (LO). In this way, the signal is downconverted from the optical carrier frequency (several hundreds of THz) to a microwave carrier frequency (a few GHz). The resulting beat signal after the photo detection exhibits a center frequency which corresponds to the intermediate frequency f_{IF} (IF) which is the difference between the signal frequency and the LO frequency.

The main building blocks of the heterodyne coherent receiver are:

1. Optical local oscillator laser
2. Optical coupler
3. Balanced photodetector
4. Phase/frequency locking
5. Polarization control loop
6. Electrical signal processing

To achieve high receiver sensitivity in a coherent system, the following parameters have to be fulfilled [3]:

1. High power, optical local oscillator with low relative intensity noise (RIN) and low laser linewidth.
2. Balanced photodetector with high responsivity, high optical power handling capacity, and good common-mode rejection ratio (CMRR) [2].
3. Phase/frequency locking to reduce the phase and frequency noise of the intermediate frequency.

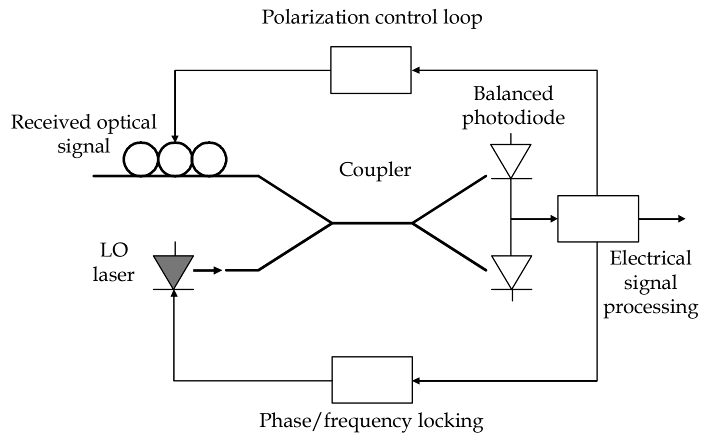


Fig. 4: General block diagram of an optical coherent receiver [4].

In this paper we consider heterodyne detection. The coherent optical transmission system used for our measurements is shown in fig. 5. The signal laser was a distributed-feedback (DFB) laser operating at an optical frequency of 193.4 THz. The following $LiNbO_3$ Mach-Zehnder modulator was driven by 2.5 Gb/s and 10 Gb/s non-return-to-zero (NRZ) electrical pseudo-random bit sequence (PRBS) of length 2^{31}-1. The MZM was biased at quadrature and the swing of the electrical drive voltage was adjusted for V_π. This produced an on-off keyed (OOK) signal with NRZ pulse shape. The extinction ratio of the modulated signal is 12 dB. After passing the optical signal through a variable optical attenuator (VOA) it was combined with the output of the local oscillator DFB laser by a 3 dB fiber coupler. We used a polarization controller to align the state of polarization of the input signal with the LO signal. It has been shown that commercially available automated polarization stabilizers can be used for this application [5]. The LO power was 14 dBm. An optical delay line was inserted after one of the coupler outputs to adjust the path length of the two optical outputs which feed the balanced photodetector. The excess insertion loss from the signal input of the coupler to the input of the two photodiodes of the balanced detector was 1.2 dB and 1.6 dB, respectively.

For the 2.5 Gb/s system a balanced photodetector with a bandwidth of 15 GHz was used. It had a responsivity of 0.75 A/W at 1550 nm. The maximum optical peak current is 20 mA. The common-mode rejection ratio (CMRR) is better than 35 dB over the whole detector bandwidth [2]. For the 10 Gb/s set-up a balanced photodetector with a bandwidth of 35 GHz was used. The maximum optical peak current for this device is 13 mA. All the other parameters are similar to the 15 GHz bandwidth balanced photodetector. After an RF amplifier with high gain and 4.5 dB noise figure (NF), the signal was split for a signal path and a loop path. A phase locked loop (PLL) was implemented to lock the intermediate frequency (IF) beat at exactly 10 GHz and 27.5 GHz, respectively, for the 2.5 and 10 Gb/s system. The PLL also allowed active narrowing of the IF beat linewidth. After IF to baseband conversion of the heterodyne signal, the signal was lowpass filtered. The filter had a cutoff frequency of 2 GHz and 7.5 GHz, respectively for the 2.5 and 10 Gb/s system. After clock-and data recovery (CDR), the bit-error rate (BER) was measured with a BER tester.

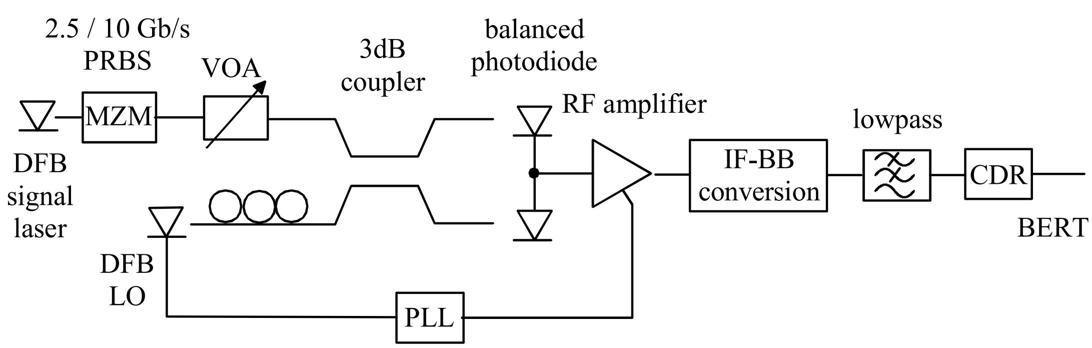


Fig. 5: Coherent optical transmission setup. Please note that there is no EDFA in this system set-up.

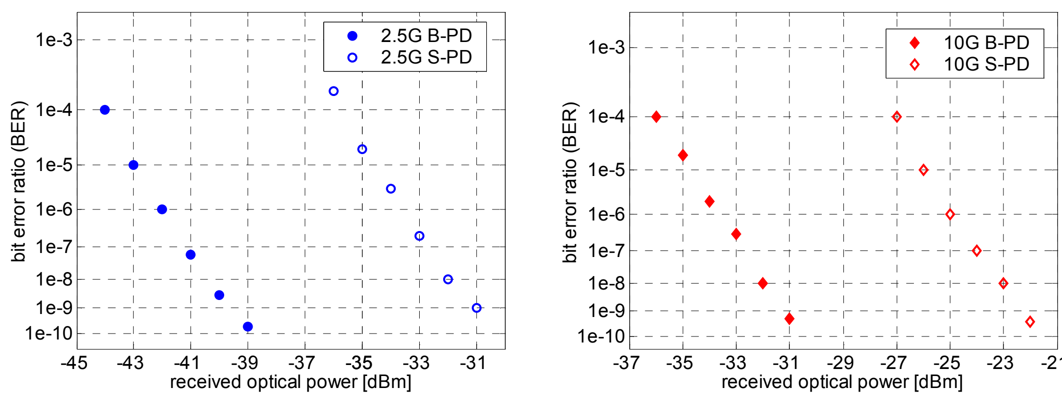
4. 1.55 µm COHERENT OPTICAL RECEIVER RESULTS

To measure the sensitivity of the coherent receiver, we varied the optical signal input power by the variable optical attenuator. In the case of a single photodiode (S-PD) we only used one of the two optical inputs of the balanced photodiode (B-PD). The sensitivities of 2.5 Gb/s and 10 Gb/s NRZ-OOK for single-ended and balanced detection are shown in fig. 6. The sensitivities for a BER of $1 \cdot 10^{-9}$ are summarized in table 1.

Table 1. Measured unpreamplified sensitivity at $1 \cdot 10^{-9}$ with coherent receiver for 2.5 Gb/s and 10 Gb/s NRZ-OOK.

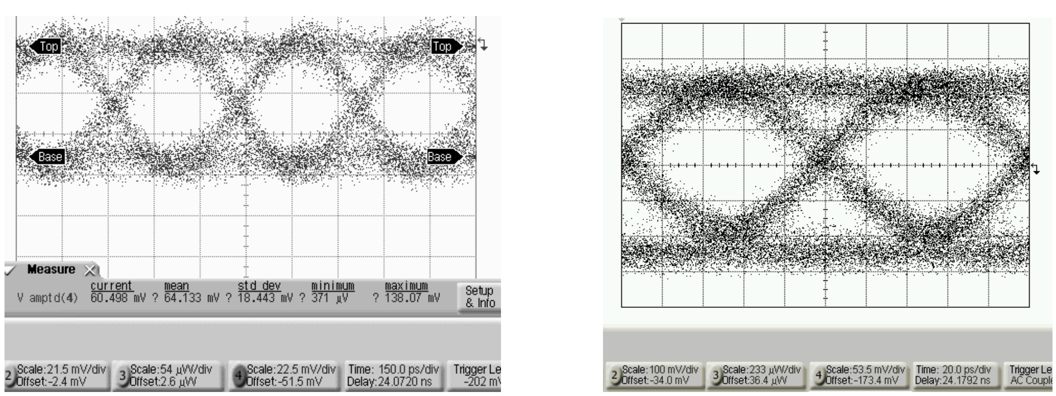
Device Type	2.5 Gb/s	10 Gb/s
Single PD	-31 dBm	-22 dBm
Balanced PD	-40 dBm	-31 dBm

The improvement by using the balanced photodiode is 9 dB for both 2.5 Gb/s and 10 Gb/s. We explain this by the relative intensity noise (RIN) cancellation of the LO laser with the balanced receiver which we investigate in more detail in section 5. The received eye diagrams for 2.5 Gb/s and 10 Gb/s NRZ-OOK are given in fig. 7.



(a) (b)

Fig. 6: Measured unpreamplified sensitivity with coherent receiver: (a) for 2.5 Gb/s and (b) for 10 Gb/s NRZ-OOK detected with balanced photodiode (B-PD) and single photodiode (S-PD).



(a) (b)

Fig. 7: Eye diagrams of coherent receiver: (a) 2.5 Gb/s at -40dBm signal input, and (b) 10 Gb/s NRZ-OOK at -31 dBm signal input.

The measured IF spectrum for 10 Gb/s operation is shown in fig. 8.

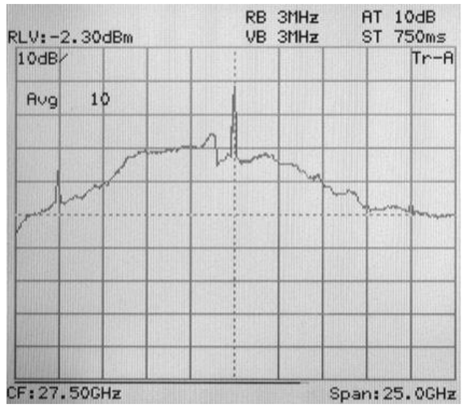


Fig. 8: Measured IF spectrum of 10 Gb/s NRZ-OOK.

For the described heterodyne detection the shot noise limit for OOK for an error probability of 1E-9 is 40 photons/bit. Our measured results are 12 dB away from the LO shot noise limit. The difference between measured results and the shot noise limit can be attributed to 48% quantum efficiency of the photodetector as well as the excess loss of the coupler and the subsequent connectors. The insertion losses can be reduced when the outputs of the coupler are adjusted and directly spliced to the inputs of the balanced detector. Moreover the RF amplifier adds extra thermal noise which further introduces a noise penalty. For best receiver sensitivity, the bandpass filter (the combined frequency response of the photodetector and the RF amplifier) has to correspond to the matched filter. Un-canceled relative intensity noise (RIN) of the LO laser also has to be considered [4]. No penalties from a finite IF linewidth are expected since the linewidth-to-bit-rate ratio is much less than 0.002 [6]. Finally, intersymbol interference and jitter introduced by the electrical data chain also lead to degradations in the sensitivity.

5. RELATIVE INTENSITY NOISE CANCELLATION

The results given in fig. 6 indicate that the receiver sensitivity of the coherent optical system can significantly be improved by using a balanced photodetector instead of a single-ended photodetector. One reason for this improvement is the cancellation of relative intensity noise (RIN) of the optical LO laser. RIN manifests itself by intensity fluctuations of the laser. The setup to measure the RIN is given in fig. 9.

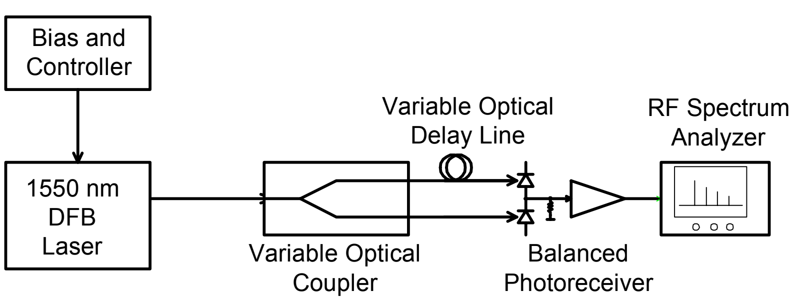


Fig. 9: Setup to measure the impact of relative intensity noise induced by a DFB laser using single-ended and balanced detection.

Since the power of the optical LO is much higher than the power of the received optical signal, intensity fluctuations (RIN) of the optical LO can cause significant degradation. As shown in this section, this common-mode noise can be eliminated by means of a balanced photodetector.

The DFB laser can be operated at different drive currents, which allows changing the amount of RIN induced by the laser. A lower drive current causes higher relative intensity noise levels and vice versa. The output signal of the laser is fed to a variable ratio optical coupler. The two outputs of the couplers are connected to the inputs of a balanced photodetector. The variable optical delay line is used to guarantee the same path length for the input signals into the balanced photodetector. By adjusting the coupling ratio from 50/50 to 0/100, both balanced and single-ended detection can be achieved with the setup. The signal out of the photodetector is electrically amplified and measured with a RF spectrum analyzer. Results of this measurement setup are shown for a high RIN value of -130 dB/Hz in fig. 10 and for a low RIN value of -160 dB/Hz in fig. 11.

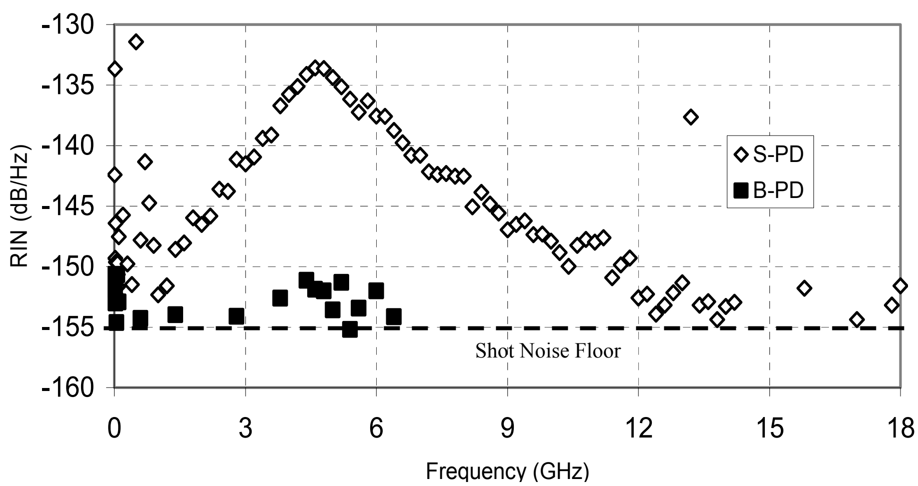


Fig. 10: Measured RIN values of DFB laser with 2.5 dBm output power for single-ended and balanced detection. It can be seen that RIN values of -130 dB/Hz can be reduced to levels below -150 dB/Hz over a bandwidth of 18 GHz.

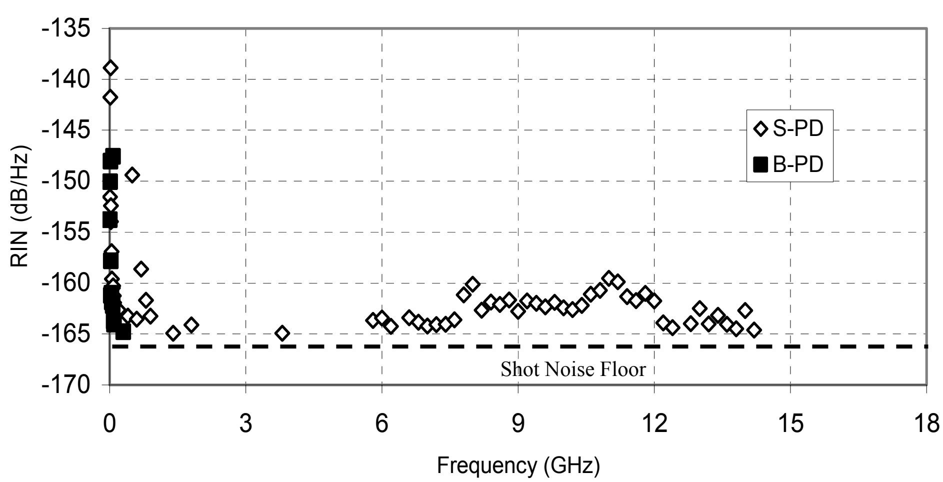


Fig. 11: Measured RIN values of DFB laser with 11.5 dBm output power for single-ended and balanced detection. It can be seen that RIN values of -160 dB/Hz are reduced to levels below the shot noise floor.

Balanced detection reduces the RIN levels from -130 dB/Hz by at least 20 dB to levels of -150 dB/Hz over a bandwidth of 18 GHz. If the RIN level of the DFB laser is as low as -160 dB/Hz the balanced photodetector suppresses the RIN below the shot noise floor. Note that the shot noise floor, which decreases with increasing DC photocurrent, is reduced from -155dB/Hz for the 2.5 dBm case to -165dB/Hz for the 11.5 dBm case.

The results of figs. 10 and 11 demonstrate the good common-mode rejection of the balanced detector. They also explain why the receiver sensitivity of the coherent optical system is increased significantly by using a balanced photodetector.

6. AUTOMATIC FREQUENCY CONTROL LOOP

For stable operation, the coherent receiver must be able to respond to frequency drifts of the signal laser. If the frequency control loop is locked, the LO tracks frequency changes of the signal laser to provide a stable IF frequency. The maximum measured frequency drift in our experimental setup is approximately 300 MHz. With the locking range of our frequency locked loop of 400 MHz, it is able to track the frequency drift. The frequency locked loop was able to track the frequency drift of the signal laser over a time frame of more than 2 days. In a locked operation, the IF linewidth is as low as 130 Hz as shown in fig. 12. This compares with the open loop linewidth (determined by the aggregate linewidth of the signal and LO laser) of 1 MHz. Please note that the IF beat frequency is always down-converted to 10 GHz so that the control loop can operate at a fixed frequency.

Since the balanced photodetector can detect wavelengths from 850 to 1650 nm the same coherent receiver can be used to receive any optical signals in this wavelength range by changing the wavelength of the LO laser. To accommodate different operational wavelengths of a telecom system, a widely tunable laser LO with a wider tuning range than a DFB laser is required.

If WDM transmission is considered (e.g. to increase the data capacity of the system) it is also necessary to select the desired WDM channel. This task is also accomplished by our automatic frequency control. In this case the LO frequency is automatically tuned until the IF beat is found at the desired frequency. The tuning range of the coherent receiver is determined by the LO laser. For most DFB lasers it is 2 nm. The tuning range may be extended to cover the whole C-band by using a widely tunable laser as an LO.

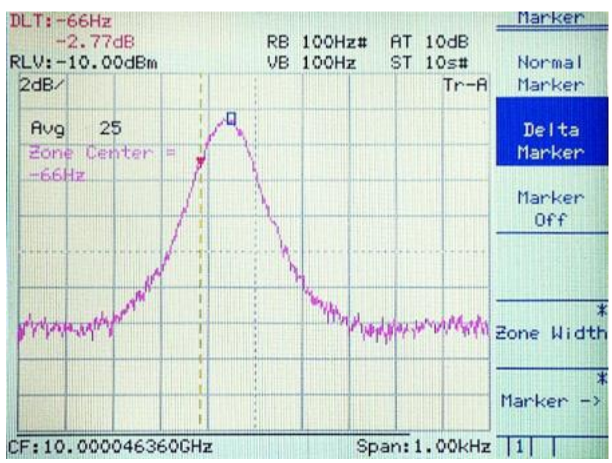


Fig. 12: Using an optimally designed PLL, the coherent optical receiver demonstrates a measured IF linewidth of 130 Hz.

7. CONCLUSION

The performance of a 1.55 µm unpreamplified coherent optical transmission system has been investigated by experiment. It shows very high receiver sensitivities of -31 dBm for 10 Gb/s transmission and -40 dBm for 2.5 Gb/s transmission. This high receiver sensitivity was realized by using a balanced photodetector which cancels the relative intensity noise of the high power optical local oscillator laser and improves system sensitivities by 9 dB. To deploy the coherent optical receiver, an automatic frequency control loop was implemented which shows excellent performance. This control loop allows for a robust and field deployable receiver.

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