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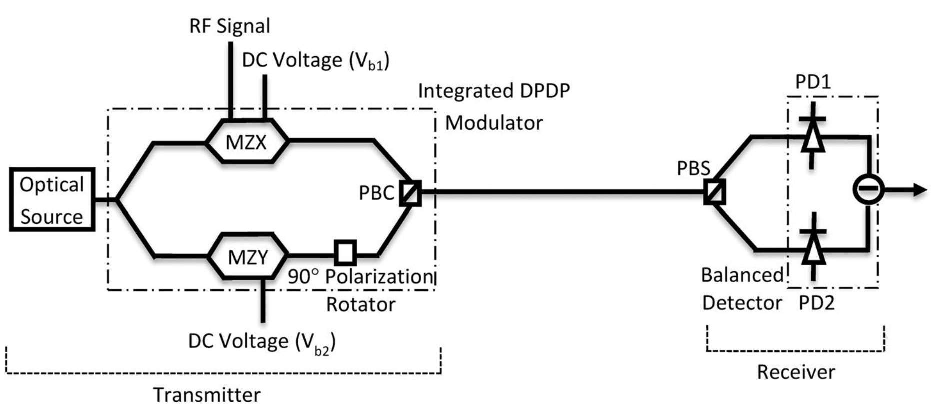

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Intensity Noise Suppression Using Dual-Polarization Dual-Parallel Modulator and Balanced Detector

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Abstract: A new structure for suppressing the relative intensity noise (RIN) from an optical source is presented. It is based on an integrated dual-polarization dual-parallel modulator and a balanced detector. It only requires a single fiber connected between the transmitter and the receiver whereas two fibers are required in the conventional dual-output modulator based RIN suppression structure. Experimental results demonstrate RIN suppression of >10 dB over 1–16 GHz frequency range with and without RF signal modulation.

Index Terms: Fiber optic links, noise suppression, balanced detection, optical modulators, optical fiber communication.

1. Introduction

The performance of a fibre optic link for transmitting an analog RF/microwave signal has been studied extensively. Link gain, noise figure and dynamic range are the figures of merit of a fibre optic link [1]. Both the noise figure and the dynamic range are dependent on the noise presented in the system. Relative intensity noise (RIN), shot noise and thermal noise are the three noise components in an unamplified fibre optic link. RIN is due to intensity fluctuation of the light generated by an optical source, which is caused by spontaneous emission. It is proportional to the square of the average optical power into the photodetector (PD). On the other hand, the shot noise is proportional to the average optical power into the PD and the thermal noise is independent of the average optical power. Therefore, RIN is usually the dominant noise source in the system when a high-power optical signal into the PD, which is required to obtain a high link gain.

RIN is also dependent on the RIN parameter of the optical source used in the system. Today commercial DFB lasers have a high power of 16 dBm and a low RIN parameter of <-160 dB/Hz [2]. This results in the RIN to be higher than the shot noise for >6 dBm average optical power into the PD as shown in Fig. 1. Typical commercial wavelength tunable lasers have a RIN parameter of -145 dB/Hz [3]. In this case, RIN is the highest noise component in the system for >-3.9 dBm average optical power into the PD. Optical sources such as spectrum sliced amplified spontaneous emission (ASE) noise sources and super luminescent diodes are important in passive optical networks [4], microwave photonic signal processing [5] and optical coherence tomography [6]. These optical sources have a high RIN parameter compared to DFB lasers. Fig. 1 shows an optical

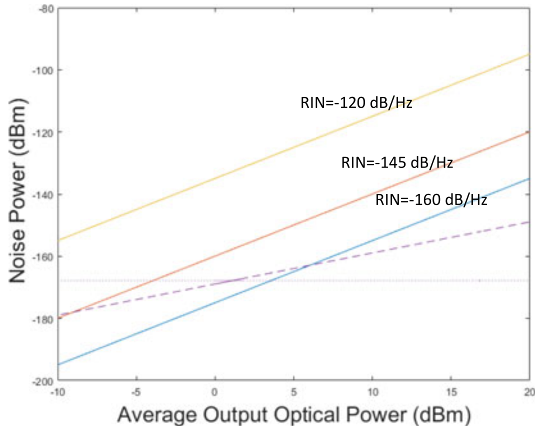


Fig. 1. RIN (solid line), shot noise (dashed line) and thermal noise (dotted line) of a fibre optic link formed by an optical source, an optical modulator and a photodetector.

source with a RIN parameter of −120 dB/Hz causes RIN to be much higher than the shot and thermal noise even for a low-power optical signal into the PD. It should be pointed out that the RIN from an optical source with a high RIN parameter also dominates the signal spontaneous beat noise from an optical amplifier, when an optical amplifier is used in the system to compensate for the system loss.

Various techniques have been proposed for RIN suppression. These include using a gain saturated semiconductor optical amplifier [4], delayed differential detection [7] and balanced detection [8]–[10]. Balanced detection is the most common approach for RIN suppression. It can also be used to suppress the noise generated by an optical amplifier [11] and the phased induced intensity noise generated by a delay line signal processor [12]. The conventional balanced detection technique requires a dual-output modulator that generates two 180° phase difference RF modulated optical signals. The two RF modulated optical signals are added while the RIN is suppressed at a balanced detector. The drawback of using a dual-output modulator in the balanced detection technique is that it requires fibre length matching and optical power matching between the transmitter and the receiver, which is difficult for a long fibre optic link. Delayed differential detection can overcome this problem but large RIN suppression can only be achieved in a narrow frequency range.

This paper proposes for the first time that using an integrated dual-polarisation dual-parallel (DPDP) modulator and a balanced detector to suppress the RIN. This eliminates the requirement of long distance fibre length matching. Optical power matching can be accomplished by controlling a bias voltage in the DPDP modulator. The new RIN suppression structure is analysed and is verified experimentally.

2. Operation Principle and Analysis

Figure 2 shows a new structure for RIN suppression. The optical source, which can be a laser, a LED or a spectrum sliced ASE noise source, generates a continuous wave light into an integrated DPDP modulator. The light is equally split into two, where one is modulated by an RF signal in a quadrature-biased Mach Zehnder modulator (MZM) (MZX) and the other is passed through another MZM (MZY) without RF signal modulation. MZY is biased close to the quadrature point. The polarisation state of the light at the output of MZY is rotated by 90° via a 90° polarisation rotator. It is combined with the RF modulated optical signal from MZX output via a polarisation beam combiner (PBC). The DPDP modulator output optical power is given by

$$P_o = \frac{t_{ff} P_{cw}}{4} \left[\left(1 - \sin\left(\beta_{RF} \sin \omega_{RF} t\right)\right) \hat{x} + \left(1 + \cos \beta_{b2}\right) \hat{y} \right] \tag{1}$$

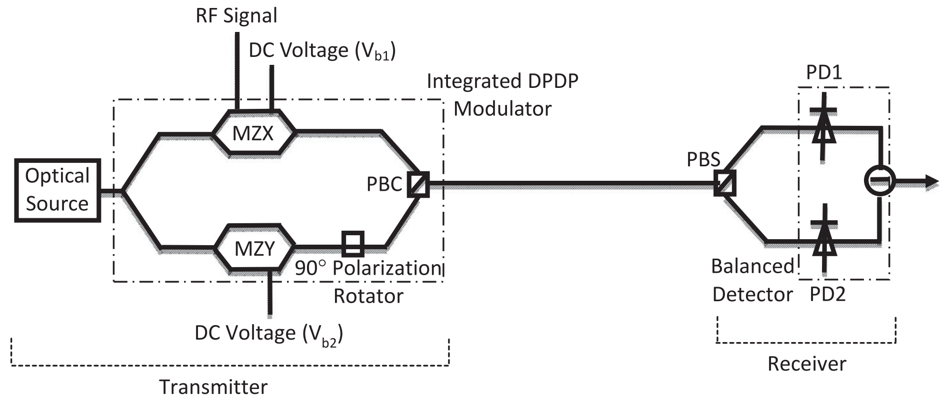


Fig. 2. New RIN suppression structure using an integrated dual-polarisation dual-parallel modulator and a balanced detector.

where t_{ff} is the insertion loss of each MZM inside the DPDP modulator and is assumed to be the same for the two MZMs, P_{cw} is the continuous wave light power into the DPDP modulator, $\beta_{RF} = \pi V_{RF}/V_\pi$ is the modulation index, V_{RF} is the voltage of the RF signal into the modulator, V_π is the modulator switching voltage, ω_{RF} is the RF signal angular frequency, $\beta_{b2} = \pi V_{b2}/V_\pi$, V_{b2} is the bias voltage into MZY, and $\hat{x}$ and $\hat{y}$ are the polarisation states representing light travelling in the slow and fast axis respectively. The two orthogonally polarised light components where one is modulated by an RF signal are transmitted by a single fibre from the transmitter to the receiver. A polarisation beam splitter (PBS) is used at the receiver to split the two orthogonally polarised light so that the light, which is modulated by an RF signal and is aligned to the slow axis, is detected by PD1 and the unmodulated light aligned to the fast axis is detected by PD2 as shown in Fig. 2. The photocurrents generated by the two PDs are given by

$$I_{PD1} = \frac{\Re t_{ff} P_{cw}}{4} [(1 - \sin(\beta_{RF} \sin \omega_{RF} t))] \tag{2}$$

$$I_{PD2} = \frac{\Re t_{ff} P_{cw}}{4} [(1 + \cos \beta_{b2})] \tag{3}$$

where $\Re$ is the PD responsivity. The two photocurrents given in (2) and (3) are subtracted at the balanced detector. Since the photocurrent at the output of PD2 does not contain an RF signal, the photocurrent at the RF signal angular frequency ω_{RF} after balanced detection can be obtained from (2) and is given by

$$I_{RF} = \frac{-\Re t_{ff} P_{cw} J_1(\beta_{RF})}{2} \tag{4}$$

where $J_n(x)$ is the Bessel function of nth order of first kind. Both the RIN and the shot noise are dependent on the average photocurrent at the output of PD1 and PD2, which are given by

$$I_{avg,PD1} = \frac{1}{4} \Re P_{cw} t_{ff} \tag{5}$$

$$I_{avg,PD2} = \frac{1}{4} \Re P_{cw} t_{ff} (1 + \cos \beta_b) \tag{6}$$

Matching the two average photocurrents is required for RIN suppression. Equation (6) shows biasing MZY at the quadrature point can equalise the two average photocurrents. Practical systems have polarisation dependent loss and the losses in the two arms of the DPDP modulator are different. These alter the two average photocurrents. Controlling the bias voltage of MZY inside the DPDP modulator enables optical power matching, which leads to average photocurrent matching, i.e., $I_{avg,PD1} = I_{avg,PD2}$, for RIN suppression. The amount of RIN suppression is also dependent on the balanced detector common mode rejection ratio and the RF modulation index [13]. The total noise power at the output of the new RIN suppression structure when two equal-amplitude RF signals into MZX can be written as

$$N_{total} = RIN \cdot I_{avg}{}^{2} R_{out} B(S + 4\beta_{RF}^{2}) + 2(2qI_{avg} R_{out} B) + 2(KTB) \quad (7)$$

where *RIN* is the RIN parameter of the optical source, $I_{avg} = I_{avg,PD1} = I_{avg,PD2}$ after optical power matching, R_{out} is the PD load resistance, S is related to the balanced detector common mode rejection ratio and is 0 in the ideal case, B is the noise bandwidth, q is the charge of an electron, K is the Boltzmann's constant and T is the absolute temperature. The spurious free dynamic range (SFDR) of the new RIN suppression structure is given by

$$SFDR = \left(\frac{\frac{1}{32} \Re^{2} t_{ff}{}^{2} P_{cw}{}^{2} m_{TOI}{}^{2} R_{out}}{N_{total}} \right)^{\frac{2}{3}} \quad (8)$$

where $m_{TOI} = \sqrt{8}$ is the modulation index at the third-order intercept point [14]. Equation (8) shows suppressing the RIN in a RIN-dominant system improves the system SFDR performance. The amount of SFDR improvement is determined by the amount of RIN suppression. Reference [15] shows a high SFDR of $>$119.5 dBHz$^{2/3}$ can be obtained experimentally in a dual-output modulator based balanced detection structure.

Since the two MZMs together with the 90° polarisation rotator are integrated on the same substrate, the output of the DPDP modulator is guaranteed to be two orthogonally polarised optical signals. The polarisation states of these two optical signals change as they travel through a standard single mode fibre connected between the transmitter and the receiver. However, their polarisation states remain orthogonal. The polarisation states of the two orthogonally polarised optical signals at the PBS input need to be aligned to the slow and fast axis to ensure each one of them is detected by only one photodetector. This requires a polarisation maintaining fibre between the DPDP modulator and the PBS. Alternatively, a standard single mode fibre and a polarisation stabiliser [16] in front of the PBS can be used. The polarisation stabiliser relies on a feedback control circuit to maintain a stable output polarisation against fluctuations in input polarisation state. In practice, DPDP modulators suffer a bias drift problem as in all electro-optic modulators. This causes mismatch in the two average optical powers into the balanced detector. A modulator bias controller, which is also based on a feedback control circuit, can be used to overcome this problem. Commercial modulator bias controllers [17] have the ability to lock the bias point to any point in the modulator transfer characteristic. Using a bias controller and a polarisation stabiliser in the new RIN suppression structure enables accurate average output optical power matching. Since the two orthogonally polarised optical signals travel through the same fibre from the transmitter to the receiver, only short fibre length matching is required between the PBS and the balanced detector for RIN suppression. Note that regardless whether a standard single mode fibre or a polarisation maintaining fibre is used to connect between the transmitter and the receiver in the RIN suppression structure presented in Fig. 2, the two orthogonally polarised light arrived at the receiver have a time delay difference. This is due to polarisation mode dispersion (PMD) in optical fibres causing group velocity variation with polarisation states. By simply designing the two path lengths between the PBS and the PDs based on the PMD and length of the fibre between the transmitter and receiver can eliminate this time delay difference. This ensures the two orthogonally polarised light arrived at the PDs at the same time to obtain large RIN suppression.

3. Experimental Results

Experiments have been set up to demonstrate RIN suppression in the DPDP modulator based RIN suppression structure. The optical source was a spectrum sliced ASE noise source. It was implemented by an erbium doped fibre amplifier (EDFA) followed by a 0.5 nm bandwidth optical filter and a polariser which blocked light travelled parallel to the fast axis. The optical power of the spectrum sliced ASE noise after the polariser was −4.1 dBm. It was amplified by another EDFA

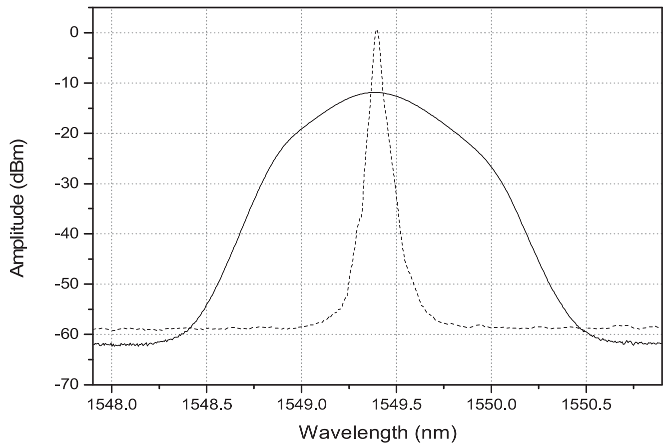


Fig. 3. Spectrum of the amplified spectrum sliced ASE noise (solid line) and the wavelength tunable laser (dashed line) measured on an optical spectrum analyser. The average optical power into the optical spectrum analyser was 2.1 dBm.

with 3.8 dB noise figure. This was followed by a 1 nm bandwidth optical filter, which was used to suppress the spontaneous-spontaneous beat noise from the optical amplifier. The spectrum of the amplified spectrum sliced ASE noise source was measured on an optical spectrum analyser and is shown in Fig. 3. The spectrum of a wavelength tunable laser with a linewidth of less than 100 kHz is also included in the figure. The spectrum sliced ASE noise had a 3-dB linewidth of 0.47 nm. The RIN parameter of the amplified spectrum sliced ASE noise source was obtained by connecting the output of the noise source to a PD, which generates 4.4 mA photocurrent into an 18 GHz bandwidth amplifier. The RIN power of the amplified spectrum sliced ASE noise source was measured on a signal analyser. The RIN power of the tunable laser with the optical spectrum as shown in Fig. 3 was also measured under the same condition for comparison. It was found to be −89.9 dBm for a 10 kHz signal analyser resolution bandwidth. The tunable laser RIN parameter of −150.1 dB/Hz was obtained using the measured RIN power and the RIN power expression [18], which agrees with the RIN parameter of <-145 dB/Hz provided by the tunable laser manufacturer. The RIN parameter of the amplified spectrum sliced ASE noise source was obtained using the same process as the tunable laser RIN parameter measurement and was found to be −114.9 dB/Hz. Simulation results obtained using the measured RIN parameter value and other experimental parameter values such as −4.1 dBm spectrum sliced ASE noise power into an EDFA and 3.8 dB EDFA noise figure, show the RIN was 26 dB above the signal spontaneous beat noise from the EDFA. The signal spontaneous beat noise becomes the highest noise component in the system when the optical source RIN parameter is <-142 dB/Hz.

The continuous wave light with an average optical power of 16 dBm from the amplified spectrum sliced ASE noise source was launched into a DPDP modulator (Fujitsu FTM7980EDA) via a polarisation controller. MZX inside the DPDP modulator was biased at the quadrature point and was driven by an RF signal from a microwave signal generator. The output of the DPDP modulator passed through a standard single mode fibre into a polarisation controller, which was used to align the two orthogonally polarised optical signals to the slow and fast axis before entering the PBS. One of the PBS outputs was connected to a variable optical delay line for fibre length matching. Due to the lack of a balanced detector, two PDs (Discovery Semiconductors DSC30S) and a 180° hybrid coupler having a 3-dB bandwidth of 1–18 GHz were used for balanced detection. The average photocurrent at each PD output was 1.3 mA. The output RF signal together with the noise were amplified by an 18 GHz bandwidth amplifier (Keysight 87405C) before viewing on a signal analyser. Fig. 4 shows the output noise power spectrum when no RF signal was applied to the DPDP modulator and the DC bias voltage of MZY was properly adjusted for optical power matching. The figure also shows the output noise power spectrum when only one of the PBS outputs was connected to the balanced detector. It can be seen from the figure that the new RIN suppression structure

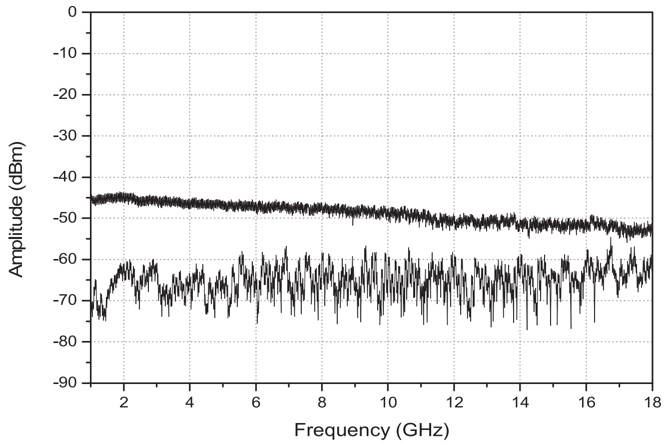
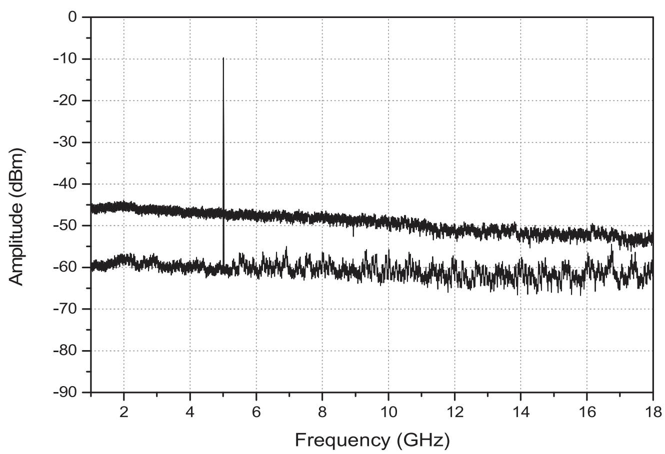
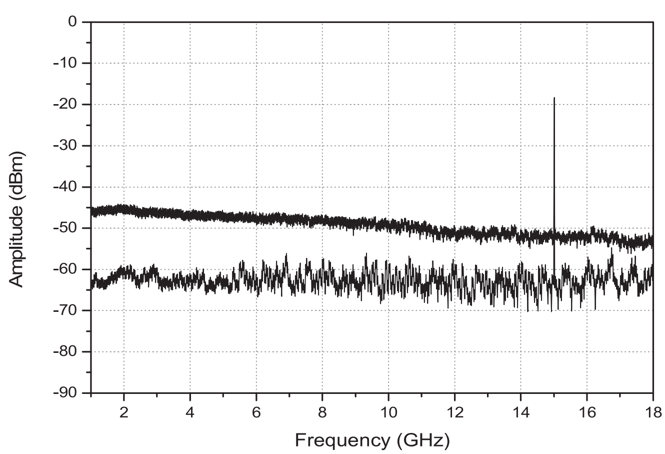


Fig. 4. The output noise spectrum of the new RIN suppression structure measured on the signal analyser in an unbalanced mode (top trace) and a balanced mode (bottom trace). Signal analyser resolution bandwidth is 510 kHz.



(a)



(b)

Fig. 5. The output spectrum of the new RIN suppression structure operated in an unbalanced mode (top trace) and a balanced mode (bottom trace). MZX was driven by (a) a 5 GHz and (b) a 15 GHz RF signal. Signal analyser resolution bandwidth is 510 kHz.

reduces the RIN by $>$15 dB at 5 GHz and $>$10 dB at 15 GHz. The reason why the amount of RIN suppression reduces at high frequencies is the 180° hybrid coupler used in the experiment has high amplitude and phase imbalanced at high frequencies, which degrades the common mode rejection ratio in the balanced detector formed by two PDs and a 180° hybrid coupler. The ripples presented in the noise spectrum shown in the bottom trace of Fig. 4 are due to the frequency response difference between the two input ports of the 180° hybrid coupler. Using a balanced detector with a high common mode rejection ratio can increase the amount of RIN suppression and eliminate the ripples in the noise spectrum. Nevertheless, the experimental results demonstrate over 10 dB RIN suppression in a 1–16 GHz frequency range. Fig. 5 shows the output of the new RIN suppression structure when MZX inside the DPDP modulator was driven by a 5 GHz and a 15 GHz RF signal with 0 dBm power. It also shows the output when the system was operated in an unbalanced mode, i.e., only the optical signal at the output of MZX into the balanced detector. It can be seen from the figures that over 10 dB RIN suppression was obtained after balanced detection. The output RF signal amplitude was the same for the system operated in both balanced and unbalanced modes.

4. Conclusion

A new structure for RIN suppression has been presented and experimentally demonstrated. It is based on an integrated DPDP modulator, which generates two orthogonally polarised optical signals. This enables a single fibre to be connected between the transmitter and the receiver. The orthogonally polarised optical signals are split by a PBS and are detected by a balanced detector for RIN suppression. Only short fibre length matching is required at the receiver for balanced detection. The DPDP modulator also has the function of controlling the average power of the unmodulated light for optical power matching, which is required for all balanced detection noise suppression systems. More than 10 dB RIN suppression in a wide frequency range of 1–16 GHz has been demonstrated.

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