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JITTER IN ANALOG OPTICAL LINKS USING A QUADRATURE-BIASED MACH–ZEHNDER MODULATOR

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ABSTRACT: *Characteristics of jitter have been investigated in a 10-GHz analog optical link using a quadrature-biased Mach–Zehnder modulator followed by an erbium-doped fiber amplifier (EDFA) and a PIN photodiode. For the case of low optical input power, jitter varies inversely with input power, indicating the thermal noise limited characteristic. For high input optical power, jitter saturates at a minimum for different RF power levels for the configuration without EDFA. For the configuration using EDFA, jitter is also inversely proportional to EDFA gain but shows different minima for different input optical power with output power fixed by adjusting EDFA gain because of amplified spontaneous noise noise.* © 2012 Wiley Periodicals, Inc. Microwave Opt Technol Lett 54:2725–2727, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.27196

Key words: *analog optical link; erbium-doped fiber amplifier; jitter; quadrature bias; Mach–Zehnder modulator*

1. INTRODUCTION

Analog optical links operating in the intensity-modulation and direct-detection mode have many applications such as in signal distribution systems and antenna remoting systems [1]. The transmitters in these links have a common configuration consisting of a Mach–Zehnder modulator (MZM) followed by an erbium-doped fiber amplifier (EDFA). For broadband applications, the MZM is quadrature-biased to have the maximum linearity by eliminating second-order distortion [2]. The EDFA is used to generate high optical power for better link performance such as loss compensation and higher dynamic range.

In general, analog optical link performance has been considered in terms of gain, bandwidth, noise figure, and dynamic range. Short pulse transmission such as ultrashort optical clock, optical sampling pulse, and signals for broadband phased array antennas is increasing in analog optical links. Timing accuracy is an important factor for these cases. For example, the main beam direction changes due to timing error caused by noise in a phased array antenna system controlled by a true-time delay beam-former [3]. Therefore, we need to consider the link performance at a different perspective, jitter. Jitter is a random disturbance of signal from an ideal timing position in a short period of time and a function of noise, slew rate, bandwidth, and so forth [4]. The noise sources contributing to jitter are phase noise around the carrier frequency, spur, and broadband white noise. Noise in electronic circuits is generally modeled as a random Gaussian process and jitter is linearly proportional to the root-mean-square noise and inversely proportional to the slew rate if the noise power is much smaller than the signal power [5]. As signal-to-noise ratio (SNR) is inversely proportional to noise power, we can relate SNR with jitter. It has been known that the SNR of an optical receiver using a PIN diode varies as the square of input optical power in the thermal noise limit, which is the usual case. However, at higher optical power the relative intensity noise (RIN) of optical source sets the maximum SNR [2]. EDFA induces the phase noise due to the amplified spontaneous noise (ASE), resulting in the main beam jitter around a mean direction in an optically fed phased array antenna [6].

In this article, we investigate jitter characteristics for broadband analog optical links consisting of a laser and a quadrature-biased MZM followed by an EDFA at the transmitter, and a PIN photodiode at the receiver. In Section 2, we examine how RF power and optical power input to the MZM would influence jitter characteristics in a 10-GHz optical link. Second, the effect of EDFA gain on jitter has been studied for different optical power levels. Finally, Section 3 summarizes the article.

2. EXPERIMENTS AND DISCUSSION

The experimental setup for measuring jitter is shown in Figure 1.

A distributed feedback laser diode operating at a wavelength of 1554.93 nm with an output power of 8 mW is intensity modulated by a MZM. The RIN of the laser is −145 dB/Hz, typ. A variable optical attenuator is used to adjust the optical power level at the MZM input. The MZM is a $LiNbO_3$-based modulator operating at 1550 nm with a typical insertion loss of about 8.2 dB, V_π of 3.6 V, and an offset voltage of 2.5 V. The MZM was quadrature-biased at 4.3 V and driven by a 10-GHz RF carrier signal. Because the 10-dB electrical bandwidth of the modulator is about 16-GHz, an electrical low pass filter with a cutoff frequency of 10.2-GHz was inserted in the RF gain block to limit the system bandwidth. The overall gain and noise figure of the RF gain block were measured to be about 36.3 and 8.8 dB at 10-GHz, respectively.

Jitter was measured in both frequency and time domain. An Agilent E4440A PSA series spectrum analyzer was used for the frequency domain measurement. As the frequency range of the system is 10 MHz–10.2 GHz, we have to separate the spectral range into two regions to obtain jitter, that is, one in 9.9–10.1 GHz where the frequency dependent components are present and the other for the rest spectral region where only white noise is present. The phase jitter $\sigma_{\Delta t_\varphi} = \frac{1}{2\pi f_0}\sqrt{2\int_{f_l}^{f_h} L_\varphi(f)df}$ in 9.9–10.1 GHz region is directly measured utilizing the phase jitter measurement option of the spectrum analyzer from the lower offset frequency of 10 Hz (f_l) to the higher offset frequency of 100 MHz (f_h) around the center frequency of 10 GHz (f_0) [7]. $L_\varphi(f)$ is the single sideband phase noise. For the rest of the frequency range, the jitter due to white noise $\sigma_{\Delta t_n}$ was calculated using the measured RF signal power and noise floor with the RF signal turned off. As the jitters at both regions are independent each other, the total jitter was then calculated using the

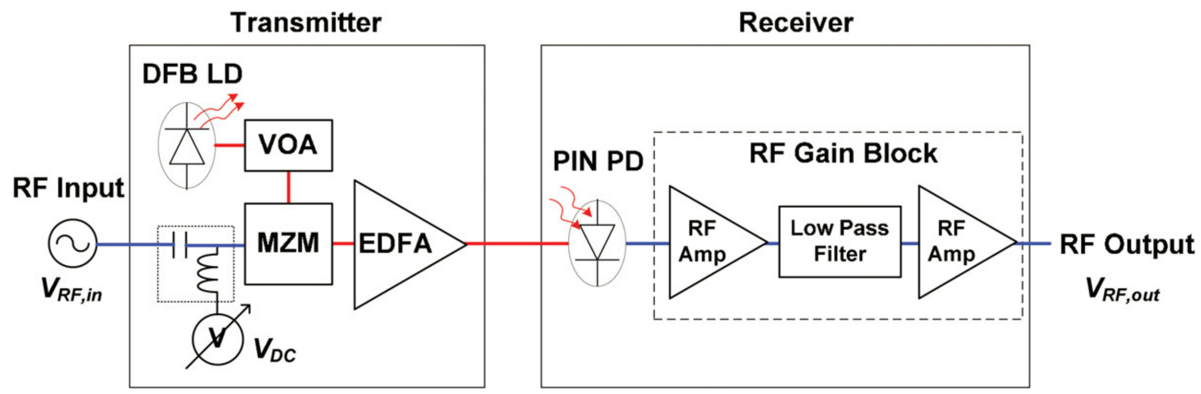

Figure 1 Experimental setup for measuring jitter in an analog optical link. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

relationship of $\sigma_{TJ} = \sqrt{\sigma^2_{\Delta t_n} + \sigma^2_{\Delta t_\varphi}}$. The total jitter which shows a normal distribution was also measured at a zero-crossing point in time domain using the histogram function of Tektronix CSA8000 digital sampling oscilloscope.

2.1. Effect of RF and Optical Power Input to MZM

To investigate the effects of RF and optical power input to MZM on jitter, an analog optical link shown in Figure 1 has been used without EDFA at the transmitter.

Figure 2 shows jitter measured as a function of laser power input to MZM at three different RF input power levels of 10, 0, and −10 dBm. The data of the RF noise spectra and the histogram measurement are designated as Noise Spectrum and Histogram in the legend, respectively. In the figure, there is a lack of histogram data for jitter great than about 10 ps because the histogram overlap occurs between two adjacent zero-crossings. Thus, the unreliable histogram data are not included in Figure 2. It is apparent that jitter becomes quieter as optical and RF power input to the MZM increase. We can find that in low optical power region jitter decreases linearly as optical power increases. For example, in the optical power region below −3 dBm for the RF power of 0 dBm, jitter becomes half as optical power doubles. This trend is found also in the optical power region below 2 dBm for the RF power of −10 dBm. In the thermal noise limited optical link using a PIN photodiode receiver, the SNR is proportional to the square of optical power. Therefore, we can see that $\sigma_{TJ} \propto P_{in}^{-1} \propto \left(\frac{S}{N}\right)^{-1/2}$. From the figure, we can also find that jitter remains the same if the optical power is reduced by 5 dB and the RF power is increased by 10 dB. The MZM modulator biased at quadrature has slope efficiency linearly proportional to the input laser optical power [2]. Therefore, as the optical power input to MZM decreases, the slope efficiency gets lower. To obtain the same jitter value, it is required to increase RF power squared for linear optical power decrease.

For the case of an optical link without EDFA, the minimum jitter was measured at the maximum optical power of 8 dBm from the noise spectra. Those were 0.38, 1.15, and 3.60 ps at RF powers of 10, 0, and −10 dBm, respectively. For higher laser power, jitter tends to saturate at a minimum similar to a maximum SNR as in the RIN limited region [2].

2.2. Effect of EDFA Gain

To investigate the effects of EDFA in the transmitter on jitter, the output power of EDFA was kept constant by varying the optical power input to and gain of EDFA. Noise figure and the saturated output power of EDFA were about 5.5 dB and 9.32 dBm, respectively.

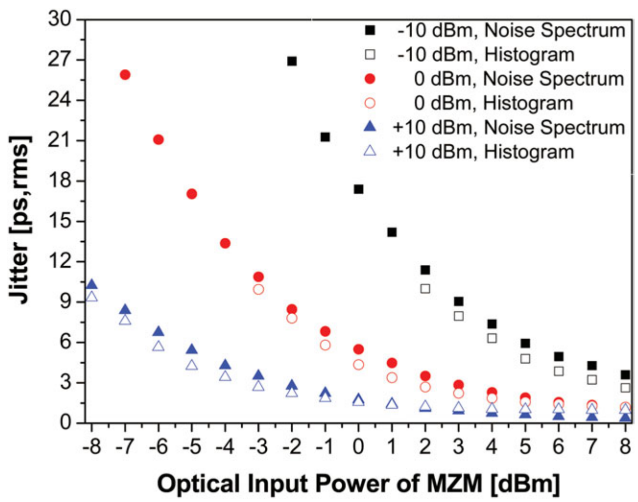

Figure 2 Measured jitter at different RF power levels as a function of the optical power input to MZM for an optical link without an EDFA. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

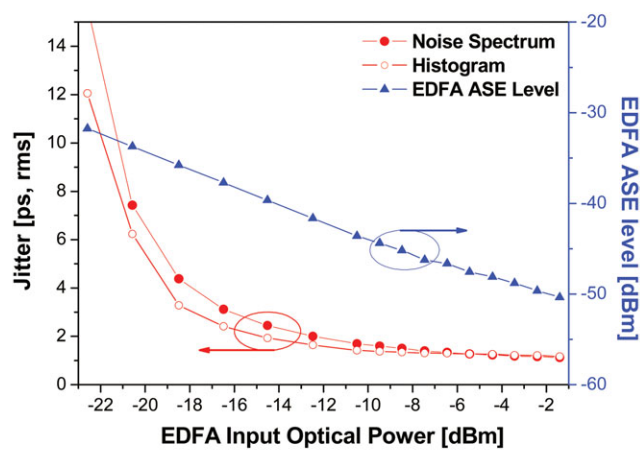

Figure 3 Jitter and ASE level measured as a function of EDFA input optical power while maintaining an optical output power level at 0.5 dBm. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

TABLE 1 Measured Minimum Jitter, EDFA Gain, and ASE Level as a Function of Optical Power Input to EDFA

EDFA Input Optical Power [dBm]	EDFA Gain [dB]	ASE Level [dBm]	Calculated Jitter from RF Spectra [ps]			Measured Jitter from Histogram σ_{TJ} [ps]
			$\sigma_{\Delta t_n}$	$\sigma_{\Delta t_n}$	σ_{TJ}	
−15.28	15.99	−38.68	2.62	0.31	2.64	2.02
−17.96	15.97	−38.64	3.33	0.35	3.35	2.60
−19.49	16.03	−38.20	4.52	0.41	4.54	4.23
−21.37	16.21	−38.36	6.43	0.47	6.45	4.96
−23.31	16.13	−38.40	8.29	0.61	8.31	6.65
−25.02	16.21	−38.58	9.91	0.89	9.95	8.69
−27.68	16.01	−38.68	14.36	1.28	14.42	

Figure 3 shows the measured jitter and ASE level as a function of EDFA input power while the output power of EDFA was maintained at 0.5 dBm. The input RF power to MZM was fixed at 0 dBm. The resolution bandwidth for the measurement of ASE level at the EDFA output was 0.1 nm. If we decrease the optical power input to EDFA, the EDFA gain should be increased to maintain a constant output power. This leads to higher ASE noise level. It is shown in the figure that jitter increases rapidly for the EDFA input optical power below about −16 dBm. This implies that EDFA gain less than 16 dB is required to keep the jitter below 3 ps for this case. When the EDFA input optical power and gain were −1.4 dBm and 1.9 dB, respectively, a minimum jitter of 1.12 ps was obtained.

Next, jitter was measured as a function of EDFA gain shown in Figure 4 with the EDFA input optical power fixed at different levels. The input RF power to MZM was fixed at 0 dBm. In the lower gain region, we can observe that jitter is inversely proportional to the EDFA gain and the 5-dB gain difference between curves at a jitter value requires the same 5-dB optical gain. It is shown that jitter decreases toward different jitter floors for different input optical power levels as the EDFA gain increases further. This phenomenon is due to the fact that the ASE level varies as the EDFA gain changes. The minimum jitters were 1.70, 2.58, and 5.02 ps for the EDFA input optical power of −10.34, −15.28, and −20.02 dBm, respectively.

Table 1 summarizes the minimum jitter, EDFA gain, and ASE level as a function of optical power input to EDFA. In the table, the jitter due to white noise is dominant because the bandwidth for white noise is 9.99 GHz in the experiment.

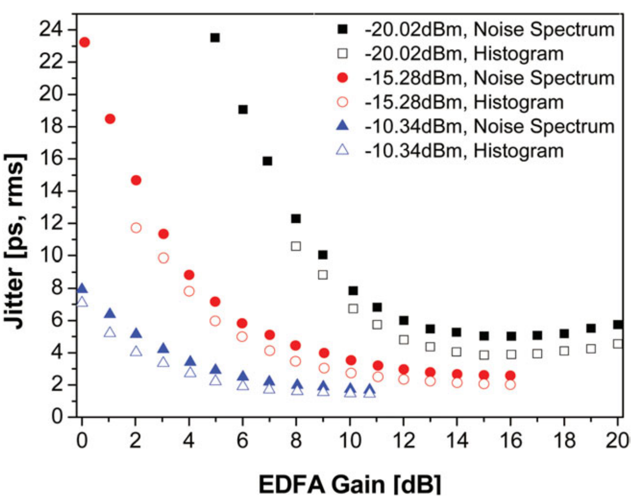

Figure 4 Measured jitter as a function of EDFA gain at different optical input power levels. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

3. SUMMARY

Jitter characteristics have been investigated for a 10-GHz analog optical link using a transmitter configuration composed of a quadrature-biased MZM followed by an EDFA and a PIN photodiode receiver. Jitter was measured in frequency domain as well as in time domain. Jitter was found to be inversely proportional to the optical power in the low optical power region which is the characteristics of the thermal noise limited optical links with a PIN photodiode receiver. In the higher optical power region, jitter tends to a minimum for different RF power levels.

The effect of EDFA used in the transmitter on jitter was also investigated by changing EDFA gain with fixed EDFA output power and RF input power. EDFA gain is proportional to ASE noise level. It is observed that jitter increases rapidly for the EDFA input optical power below about −16 dBm. When we increase the EDFA gain for the case of constant EDFA output power, jitter becomes deteriorated because of the increased ASE noise. In the lower gain region, we can observe that jitter is inversely proportional to the EDFA gain. It is also shown that jitter decreases toward different jitter floors for different input optical power levels as the EDFA gain increases further due to the fact that the ASE level varies as the gain changes. It was also observed that jitter is smaller for higher optical input power if the EDFA gain is the same, as expected.

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