Design and Simulation of an Integrated Optical Ring-Resonator Based Frequency Discriminator for Analog Optical Links

R.B. Timens, D.A.I. Marpaung[1], C.G.H. Roeloffzen, and W. van Etten

University of Twente, EWI Faculty, Telecommunication Engineering Group, PO Box 217, 7500 AE Enschede, The Netherlands

[1] Email: d.a.i.marpaung@ewi.utwente.nl

The performance of a conventional intensity modulation direct detection analog optical links is limited by the high noise power associated with large optical carrier power. This optical carrier can be suppressed by using optical frequency modulation in conjunction with a frequency discriminator. In this paper, we propose a design of an integrated optical frequency discriminator, based on optical ring resonators in order to realize an ideal Class-B optical link.

Introduction

Analog optical links (AOLs) are used in a wide variety of applications for RF and microwave signals distribution. In many applications, such as antenna beam forming and phased array systems, the links are required to convey signals over a large span of power levels, posing stringent requirements on their signal-to-noise ratio (SNR) and linearity [1]. Noise limits the minimum detectable RF-signal power while nonlinear distortion limits the maximum RF-signal power, resulting in a limited spurious-free-dynamic range (SFDR).

In a conventional intensity modulation direct detection (IMDD) link, a laser is biased for the purpose of linear operation, resulting in large average optical power. Detection of this large optical power will result in large noise power, since the dominant noise sources, RIN and shot noise, are increasing with the optical power. This, in turn, will limit the link SFDR [2]. Consequently, there is a need for links in which all received optical power contributes to the RF-signal power, i.e. links operating without a DC-bias. The ideal case of link operation without a DC-bias is known as a Class-B operation [3].

Methods to realize the ideal Class-B optical link have been the subject of considerable efforts, such as carrier reduction by low-biased operation of a Mach-Zehnder modulator, optical carrier filtering or dynamic biasing. However, all these attempts resulted in limited improvement due to an increase in nonlinearities [3].

In this paper, we propose an integrated optical ring-resonator based frequency discriminator for an optical frequency modulated link to realize the Class-B operation. The frequency discriminator converts the optical frequency modulation (FM) into optical intensity modulation (IM) such that all detected power contributes to the RF-signal power.

In the second section of this paper, the characteristics of the ideal Class-B link is discussed. This discussion evaluates the ideal Class-B link performance using the conventional IMDD link as a benchmark. In the third section, the FM AOL is discussed. This section focuses on the requirements on the frequency discriminator to obtain the Class-B operation. The fourth section is devoted to the proposed frequency discriminator. The paper closes with the conclusion and future work.

Ideal Class-B Optical Link

In an ideal Class-B optical link, the modulating RF-signal is converted into a pair of complementary half-wave rectified optical signals. The RF-signal is then restored at the receiver by means of a differential detector scheme. Since the optical power is transmitted only in the presence of a RF-signal, this will results in a zero DC-bias link operation [3]. The main difference of a Class-B optical link and the conventional IMDD optical link is that in the former, the noise depends on the RF-signal power [2], [3]. The RIN and shot noise powers per unit bandwidth in the Class-B optical link can be written as:

$$P_{\text{rin}} = RIN_{\text{laser}} \cdot I_{\text{p}}^2 \cdot R_{\text{load}} \qquad (1)$$

$$P_{\text{shot}} = 2 \cdot q \cdot I_{\text{p}} \cdot R_{\text{load}} \qquad (2)$$

where q is the electron charge, RIN_{laser} is the laser RIN power spectral density and R_{load} is the load resistance. The term I_{p} is the peak detected photocurrent defined as:

$$I_{\text{p}} = R_{\text{pd}} \cdot P_{\text{op}} \qquad (3)$$

where R_{pd} is the photodiode responsivity and P_{op} is the peak value of the complementary half-wave rectified optical signals.

To illustrate the advantage offered by the Class-B optical link, the approach in [2] is followed in which this type of optical link is constructed using a pair of directly modulated lasers. We compared the link performance with a conventional IMDD link. The parameters used in our simulations are: R_{pd} = 0.8 A/W, RIN_{laser} = -155 dB/Hz, R_{load} = 50 Ω and the laser slope efficiency, s_{l}, of 0.3 W/A. In the Class-B case, the lasers are biased at their threshold current of 15 mA, while in the IMDD case, the laser is biased at 75 mA, which is the most linear operating point.

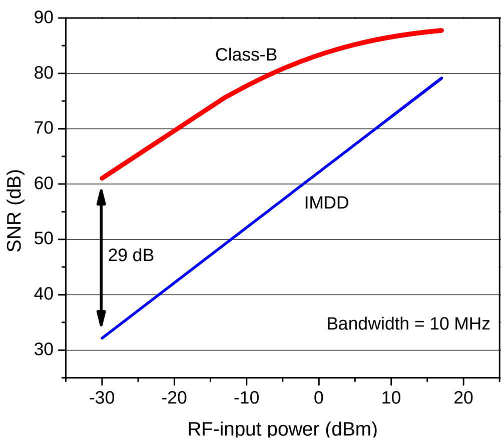

Figure 1: Simulation results of an ideal Class-B and an IMDD optical link: SNR versus RF-input power.

We simulate the SNR (in 10 MHz effective noise bandwidth) of both links and the results are shown in Figure 1. It is evident from this figure that the Class-B optical link gives a significant advantage over the conventional IMDD link in a wide range of RF-input power. Notably in the small signal region, where the SNR is premium, an impressive SNR improvement of 29 dB has been achieved. In the next section, we propose a link architecture for Class-B operation.

FM-Interferometric Detection AOL

To realize the Class-B optical link, an FM-Interferometric Detection AOL is constructed consisting of a directly modulated laser, an optical frequency discriminator and a balanced detector, as shown in Figure 2(a). In this scheme, the frequency chirping characteristic of a laser diode is exploited generating a frequency modulated optical carrier, where the instantaneous frequency deviation linearly corresponds to the instantaneous amplitude of the RF-signal. An optical filter is then used to transfer this frequency modulation back to intensity modulation. The ideal filter responses are shown Figure 2(b), where 'Branch 1' linearly converts the optical frequencies higher than f_c into intensity and 'Branch 2' does the same for frequencies lower than f_c. In this way, FM to IM conversion will yield to optical signals that comprise complementary half-wave rectified versions of the original modulating RF-signal. The balanced detector then detects the optical signals,

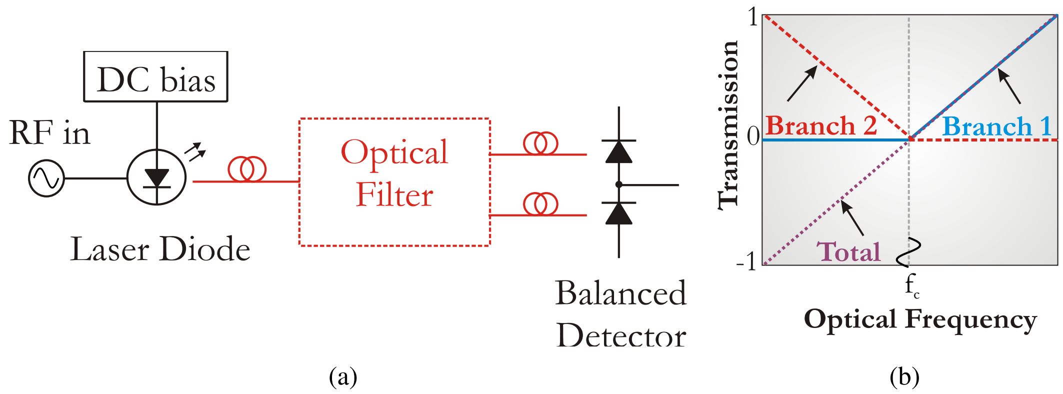

Figure 2: (a) The FM-interferometric detection AOL and (b) its ideal filter responses.

resulting in the total filter response of Figure 2(b). In the next section, we propose the filter design, based on an integrated optical chip. The advantage of using the optical chip is the potential of integrating the balanced detector and the filter in one small device.

Optical Frequency Discriminator Chip Design

The optical chip is designed based on digital signal processing concepts as discussed in [4]. In our design, we have chosen optical ring-resonators as the building block. The design constraint is to approximate the ideal response in Figure 2(b) without having an extremely complicated structure.

It is possible to approximate each desired filter branch response of Figure 2(b) using two independent rings – one cross-connected and one bar-connected ring– in series. However, using a shared ring as a power divider, instead of a 3-dB coupler, will increase the maximum transfer. Therefore, each branch consist of three rings, resulting in the design of Figure 3(a). The upper branch consists of a cross-coupled shared ring, A, and two bar-coupled unshared rings, B and C. The lower branch consists of a bar-coupled shared ring, A, a cross-coupled unshared ring, D, and a bar coupled unshared ring, E. By sharing ring A, dependencies between the filter branches are introduced for which is compensated for by the two bar-coupled unshared rings C and E. This will result in two complementary symmetric output responses as function of frequency as is shown in Figure 3(b).

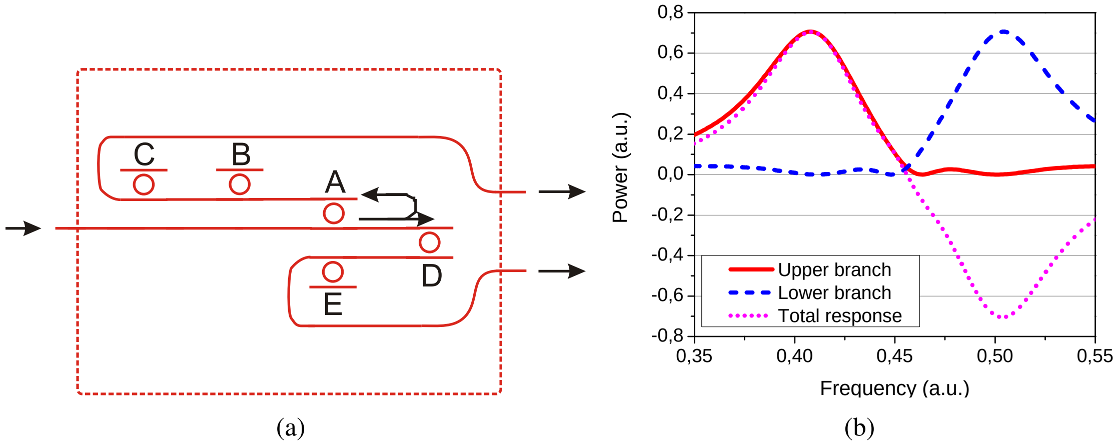

Figure 3: (a) The proposed filter design (b) and its simulated response.

By subtracting the simulated output responses an approximately linear transfer is acquired in the arbitrary frequency range of 0.4-0.5. However, in this range the individual branch transfer is not zero when the complementary branch transfer is almost linear, which will result in limited carrier suppression.

Conclusion and Future Work

FM-Interferometric Detection in AOLs is used to realize Class-B optical link operation, since this gives an considerable improvement in SFDR with respect to IMDD-links. We propose an integrated optical ring-resonator based frequency discriminator filter to obtain complementary half-wave rectified versions of the modulating RF-signal. System level simulations are currently being performed to investigate the filter performance of the proposed filter in the Class-B AOL.

References

[1] D.A.I. Marpaung, C.G.H. Roeloffzen and W. van Etten ”Dynamic Range Enhancement in Analog Optical Links with a Balanced Modulation and Detection Scheme”, *Proceedings of the International Topical Meeting on Microwave Photonics (MWP’2006)*, Grenoble, France, 3-6 October 2006, p. P10.

[2] D.A.I. Marpaung, C.G.H. Roeloffzen and W. van Etten ”A novel modulation scheme for noise reduction in analog fiber optic links”, *Proc. of the 10th IEEE/LEOS Symp. in the Benelux*, Mons, Belgium, December 2005, pp. 113-116.

[3] T.E. Darcie, J. Zhang, P.F. Driessen and J.J. Eun ”Class-B Microwave-Photonic Link Using Optical Frequency Modulation and Linear Frequency Discriminators”, *Journal of Lightwave Technology*, vol. 25, no. 1, pp. 157-164, 2007.

[4] C.K. Madsen and J.H. Zhao, Optical Filter Design and Analysis: A Signal Processing Approach, New York: John Wiley & Sons, Inc., 1999, ch. 1, pp. 1-18.