Enhanced Dynamic Range in a Directly Modulated Analog Photonic Link

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Abstract—We demonstrate a directly modulated analog photonic link (APL) capable of a high multioctave spurious-free dynamic range (SFDR). The APL consists of a pair of laser diodes, modulated in a push–pull manner, and a balanced photodetector aiming at suppressing the second-order intermodulation distortion (IMD2). In a wide frequency range of 600 MHz (2.60–3.20 GHz), an IMD2 suppression as high as 23 dB and an improvement of 5–18 dB of the second-order SFDR, relative to a conventional single arm photonic link, have been achieved. In this frequency range, the APL SFDR is in excess of 116 dB·Hz\(^{2/3}\).

Index Terms—Analog links, distortion, microwave photonics, noise, optical modulation, radio-over-fiber, spurious-free dynamic range (SFDR).

I. INTRODUCTION

THE key quantity to describe the performance of an analog photonic link (APL) is the spurious-free dynamic range (SFDR), which is defined as the maximum signal-to-noise ratio (SNR) that can be achieved while keeping the intermodulation distortion (IMD) power below the noise floor [1]. Various techniques for SFDR enhancement in APLs have been investigated [2], where most of them are directed towards external modulation using either Mach–Zehnder modulators (MZMs) [3], [4] or electroabsorption modulators [5]. While attractive in terms of performance, external modulators are more expensive compared to directly modulated laser diodes (LDs). Thus, for applications that require a very large number of APLs, for example in remoting a large-scale phased-array antenna for radio astronomy, using external modulators might become too costly. Instead, using directly modulated LDs can be advantageous owing to their low cost and simplicity.

However, applications like antenna remoting often demand a high SFDR over a multioctave signal bandwidth, of which the highest frequency component of the signal is more than twice the lowest frequency component. It is challenging to meet this requirement with directly modulated LDs because they are severely limited by the high second-order IMD (IMD2) [2], which in turn limits the multioctave dynamic range. Performance improvements can be obtained by using a linearization technique that completely suppresses the IMD2 products, leaving the third-order IMD (IMD3) as the dominant terms.

Such a linearization scheme can be implemented with an architecture consisting of a pair of LDs modulated in a push–pull manner and a balanced photodetector (BPD). This architecture was initially proposed in [6] and was later implemented for SFDR enhancements in [7]. With this so-called push–pull modulated APL, we have reported one of the highest multioctave SFDR values ever achieved with directly modulated lasers [8]. The measured APL SFDR was 119 dB·Hz\(^{2/3}\) for a signal frequency of 2.50 GHz. In this letter, we report performance optimizations of this push–pull APL in order to achieve a high SFDR over a wider frequency range.

II. PUSH–PULL MODULATED LINK

The push–pull APL architecture is shown in Fig. 1. It consists of a 180° hybrid coupler that supplies antiphase (180° out-of-phase) RF signals to a pair of LDs. In this way, the LDs are modulated in a push–pull manner. The variable optical attenuator (VOA) and the variable optical delay line (VODL) are used to control the intensity and the (RF modulation) phase of the optical signals such that upon arrival at the BPD they have the same amplitude and maintain the out-of-phase relation. The BPD simply subtracts the signals in the upper and the lower arms of the APL and restores the desired RF signal. In the ideal case of perfect amplitude and RF phase matchings, the output RF signal will be 6 dB higher compared to the case of a single arm APL [9], which can be obtained by means of disconnecting one of the optical fibers to the BPD while keeping the hybrid coupler connected. This characteristic is used in our measurements as an indication of a proper push–pull operation of the APL [10]. More importantly, all even-order distortion products at the output of the push–pull APL will be completely suppressed because the contributions from the upper and the lower arms of the APL

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are in-phase and will cancel in the BPD, as illustrated in Fig. 1. With a complete suppression of IMD2, the push–pull APL can achieve the same SFDR for both suboctave (narrowband) and multioctave (broadband) signals. The SFDR is now limited by IMD3, which is typically lower compared to IMD2 in the case of directly modulated LDs.

At a glance, the principle of operation of this push–pull modulated APL is very similar to the characteristic of a dual-output MZM link [3], [4]. The difference is that in the case of the dual-output MZM link the relative intensity noise (RIN) of the laser source is partly suppressed in the BPD [4]. In our case, there is no noise suppression because the noise from the LDs are uncorrelated and will add up incoherently at the BPD output. However, as will be shown later, we choose the bias currents of our LDs such that the RIN is already low.

III. EXPERIMENT

A. Link Realization and Optimization

We realize the push–pull APL with a pair of 1310-nm distributed-feedback (DFB) LDs from Fitel, each with a 4-GHz modulation bandwidth, and a 10-GHz BPD (Discovery Semiconductor DSC-710) consisting of a pair of PIN InGaAs photodiodes with a responsivity of 0.75 A/W. The individual lasers (marked as LD1 and LD2) were characterized prior to the demonstration of the APL link. The threshold currents of LD1 and LD2 are 9.0 and 9.5 mA, respectively, while the slope efficiencies are 0.32 and 0.37 W/A, respectively. We measured the noise power spectral densities of each LD for various bias current values, and subsequently determined their RIN. The measured RIN as a function of the bias current is depicted in Fig. 2. Beyond the bias current of 40 mA, the RIN for both LDs is already better than –155 dB/Hz. For this reason, we consider only the bias current values above 40 mA as the operating points of the push–pull APL. The detailed characterization results of the individual LDs have been reported elsewhere [8].

In actual applications, a system with a high SFDR in a wide frequency range is desirable. This implies that the APL needs to provide simultaneous IMD2 suppressions and low IMD3 powers over a broad frequency range. In the push–pull APL, the high IMD2 suppression can be obtained by properly tuning the VOA attenuation and the VODL delay such that the amplitudes of the IMD2 components in the different arms (i.e., single-arm APLs) are matched with opposite RF phases. On the other hand, the IMD3 powers can be minimized by properly selecting the LDs bias currents. These optimum bias currents are determined from the two-tone test of the individual single-arm APLs. The RF tones are 10 MHz apart and their center frequency \( f_c \) is varied from 1.0 to 4.0 GHz with a step of 100 MHz. The RF power per-tone supplied to the LDs is \(-1.5\) dBm, taking into account the 10.5-dB insertion loss of the 2 : 1 combiner and the hybrid coupler. The fundamental, the IMD2 and the IMD3 powers are measured at frequencies of \( f_c + 5\) MHz, \( 2f_c \), and \( f_c + 15\) MHz, respectively. For each \( f_c \), the bias current of each laser is varied from 40 to 85 mA. The measured IMD3 powers for each frequency and bias point are shown in Fig. 3(a) and (b) for LD1 and LD2, respectively. The lowest IMD3 powers in the frequency range of 1.0 to 4.0 GHz are obtained at bias currents of 55 mA for LD1 and 73 mA for LD2. Once the bias currents are selected, the VOA and the VODL are tuned to obtain the maximum IMD2 suppressions for the widest range of modulation frequencies.

B. Measurement Results and Analysis

The measured IMD2 suppression in the push–pull APL relative to the IMD2 powers in the individual single-arm APLs is depicted against the modulation frequency in Fig. 4. A maximum suppression of 23 dB is obtained at the frequency of 2.85 GHz. This maximum suppression can be increased by using a VOA with finer attenuation steps. The limited bandwidth of suppression is attributed to two effects. First, the IMD2 characteristics of the LDs are somewhat different. This implies that using a fixed attenuation value of the VOA (which is 2 dB in this case) is not sufficient to match the IMD2 powers of LD1 and LD2 in the whole frequency band of 1.0 to 4.0 GHz. This can be observed at the lower frequency region in Fig. 4 where the difference in the IMD2 power of the LDs can be as much as 15 dB. Second, there is a residual path length difference between the two arms of the APL which was not properly corrected by the VODL. As a result, for some modulation frequencies the IMD2 components of the LDs are not completely suppressed. These limitations can be mitigated if a pair of LDs with matched IMD2 characteristics are used and if the length of the APL arms are properly matched. An alternative scheme to avoid the need to match the length of the APL arms is proposed in [7], where two LDs with different optical wavelengths are used and their optical signals...
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IV. CONCLUSION

We have demonstrated experimentally a technique to enhance the multitone SFDR of a directly modulated APL. The technique is based on a push–pull modulation of LDs and a balanced detection for IMD2 suppression. We have shown an IMD2 suppression as much as 23 dB and a second-order SFDR improvement ranging from 5 to 18 dB, relative to the single arm photonic link, in a wide frequency range of 600 MHz (2.60–3.20 GHz). In order to achieve a higher SFDR improvement over a wider bandwidth, it is imperative to use a pair of LDs with matched IMD2 characteristics and to properly match the lengths of the APL arms. The results presented here show that the push–pull APL can be a low-cost alternative in providing a high dynamic range in broadband fiber radio applications.

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