Push-Pull Modulated Analog Photonic Link with Enhanced SFDR

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Abstract**—We demonstrate an analog photonic link (APL) with a high multioctave spurious-free dynamic range (SFDR) of 120 dB.Hz$^{2/3}$ at the frequency of 2.50 GHz. The APL consists of a pair of distributed-feedback laser diodes (DFB LDs), modulated in a push-pull manner, and a balanced photodetector aiming at suppressing the second-order intermodulation distortion (IMD2). At the frequency of 2.50 GHz, an IMD2 suppression of 40 dB, relative to the case of a single arm APL with one laser, is obtained. In a wide frequency range of 600 MHz (2.60 to 3.20 GHz), an improvement of 5 to 18 dB of the second-order SFDR relative to the single arm APL has been achieved.**

I. INTRODUCTION

A 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 of 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. In this case, the APLs will have the same SFDR for both sub-octave and multioctave signals.

In this paper, we report a linearization technique using a similar APL architecture as proposed in [6] and [7]. This so-called push-pull APL consists of a pair of LDs modulated in a push-pull manner and a balanced photodetector [8], aiming at suppression of even-order distortion products and enhancement of the multioctave SFDR. We initially optimized the system performance at the frequency of 2.50 GHz and subsequently extend the frequency range up to 3.20 GHz. We compare the push-pull APL performance with a single-arm APL consisting of one directly modulated LD and one photodetector.

II. PUSH-PULL MODULATED APL

The push-pull APL architecture for SFDR enhancement is shown in Figure 1. It consists of a 180^{o} hybrid coupler that supplies antiphase (180^{o} 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 matching, the output RF signal will be 6 dB higher compared to the case of a single arm APL [10] which can be obtained by means of disconnecting one of the optical fibers to the BPD while keeping the hybrid coupler connected. Later on, we will use

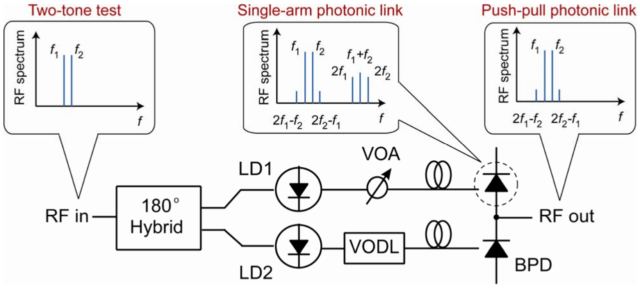

Figure 1. Schematic of a push-pull modulated APL

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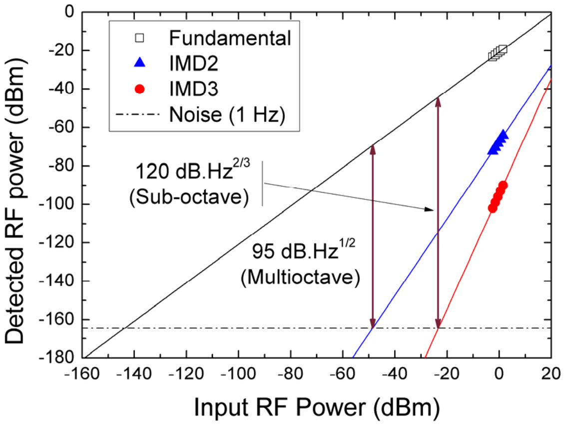


Figure 2. Measured SFDR for two tone test at 2.50 GHz and 2.51 GHz. for the single-arm APL with LD2.

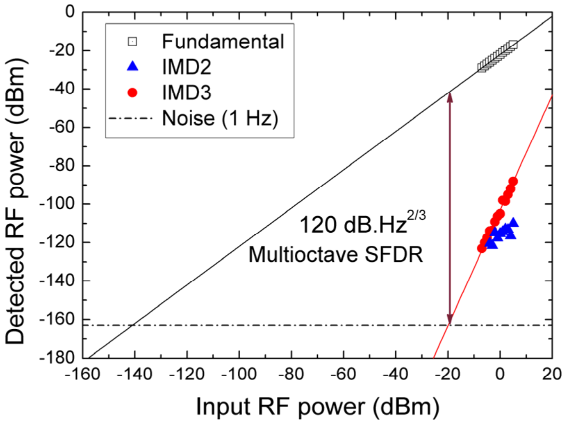


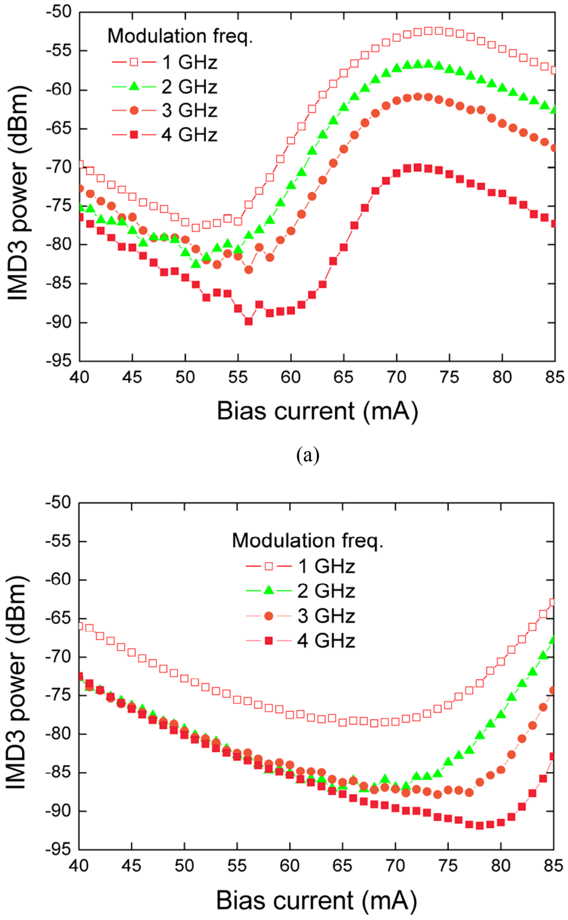
Figure 3. Measured SFDR for two tone test at 2.50 GHz and 2.51 GHz. for the push-pull APL.

this characteristic to indicate a proper push-pull operation of our link. More importantly, all even-order distortion products at the output will be completely suppressed because the contributions from the upper and the lower arms of the APL are in-phase and will cancel in the BPD, as illustrated in Figure 1. With a complete suppression of IMD2, the push-pull APL can achieve the same SFDR for both sub-octave (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 [11]. 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 low and the link is shot noise limited.

III. LINK PERFORMANCE AT 2.5 GHZ

We realize the push-pull APL with a pair of 1310 nm distributed-feedback (DFB) LDs, each with a 4 GHz modulation bandwidth, and a 10 GHz BPD consisting of a pair of PIN InGaAs photodiodes with a responsivity of 0.75 A/W. The LDs were mounted on laser diode mounts with an RF modulation capability of at least 2.50 GHz. 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 mA and 9.5 mA, respectively while the slope efficiencies are 0.32 W/A and 0.37 W/A, respectively. The detailed characterization results of these LDs have been reported elsewhere [8].

We perform two-tone measurements to characterize the link SFDR. RF tones with frequencies of 2.50 and 2.51 GHz are supplied to the lasers via a 2:1 combiner and the 180° hybrid coupler. The fundamental signal, IMD2 and IMD3 components of the output spectrum are observed at the frequencies of 2.50 GHz, 5.01 GHz and 2.52 GHz, respectively. At the selected bias points, which are 50 mA for LD1 and 51 mA for LD2, the noise power spectral densities (PSDs) of the individual APLs are sufficiently low, which amount to -166.8 dBm/Hz for LD1 and -164.5 dBm/Hz for LD2. In the push-pull APL, these noise contributions from LD1 and LD2 add up incoherently to a total noise PSD of -163 dBm/Hz. The push-pull APL is then optimized to obtain a



(a)

(b)

Figure 4. IMD3 power as a function of laser injection current for (a) LD1 and (b) LD2. The two-tone test center frequency is used as a parameter.

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maximum IMD2 suppression. This is done by means of adjusting the VOA and the delay line such that the amplitudes of the IMD2 components in the different arms (i.e. single-arm APLs) are matched with opposite RF phases. With this arrangement, IMD2 suppression in excess of 40 dB relative to the case of the individual single-arm APLs is achieved [8].

The measured SFDR for the single-arm and the push-pull APLs are shown in Figure 2 and Figure 3, respectively. The notations $SFDR_2$ and $SFDR_3$ have been used to describe the IMD2 and the IMD3-limited SFDRs, respectively. We have chosen the single-arm APL containing LD2 as the benchmark for the push-pull APL because they show higher SFDR values compared to LD1. The measured $SFDR_2$ and $SFDR_3$ for LD1 are 93 $dB.Hz^{1/2}$ and 118 $dB.Hz^{2/3}$, respectively, while for LD2 are 95 $dB.Hz^{1/2}$ and 120 $dB.Hz^{2/3}$, respectively. Hence, for multioctave signals, the dynamic range of the single-arm APLs will be limited by $SFDR_2$ which is roughly 25 dB lower than $SFDR_3$. In the push-pull APL, the IMD2 is largely suppressed and the limiting distortion is IMD3. A multioctave SFDR of 120 $dB.Hz^{2/3}$ is obtained and, to our knowledge, this value is among the highest ever reported for multioctave SFDR in directly-modulated APLs [2]. As a comparison, the same SFDR value has been cited as the highest broadband SFDR in LDs [9], which was shown with a similar architecture as our setup but at a lower frequency of 1 GHz [7].

IV. FREQUENCY RANGE EXTENSION

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 our system, the high IMD2 suppression can be obtained by properly tuning the VOA attenuation and the VODL delay, while the IMD3 powers can be minimized by properly selecting the LDs bias currents. We start the bias selection by repeating the two-tone measurements on the individual links at various frequencies and various LDs bias currents. 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 combiner and the hybrid coupler. The fundamental, the IMD2 and the IMD3 powers are measured at frequencies of f_c +5 MHz, 2 f_c and f_c +15 MHz, respectively. For each f_c, the bias current to each laser is varied from 40 to 85 mA. The measured IMD3 powers for each frequency and bias point are shown in Figures 4 (a) and 4 (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.

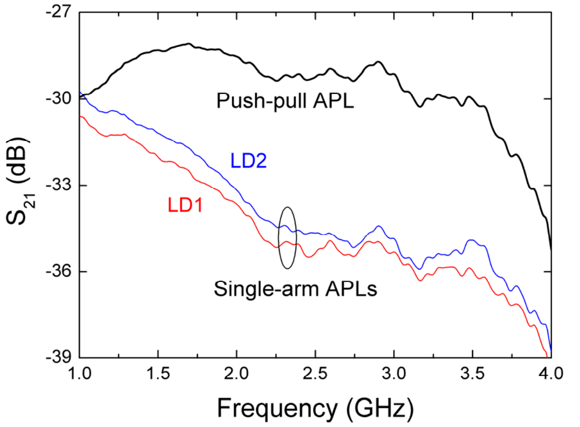

Figure 5. Fundamental signal enhancement in the push-pull APL.

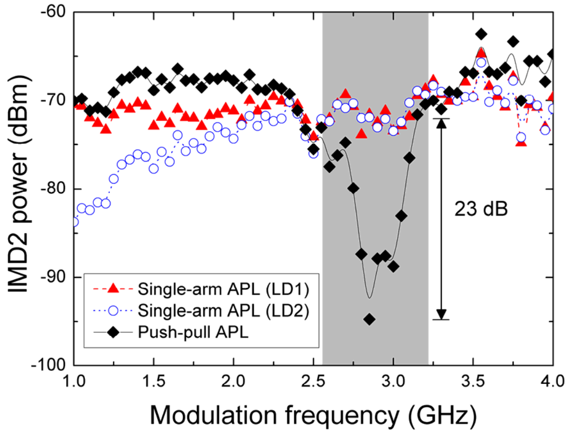

Figure 6. IMD2 suppression in the push-pull APL as function of the modulation frequency.

Next, the VOA and the VODL are adjusted to obtain large IMD2 suppressions for a wide range of modulating frequencies. The measured signal enhancement and IMD2 suppressions in the push-pull APL are depicted as functions of the modulating frequency in Figure 5 and Figure 6, respectively. A maximum signal enhancement of 6 dB relative to the individual links is obtained at a modulation frequency range of 2.0 to 3.50 GHz, while the IMD2 suppression is achieved in the modulation frequency range of 2.60 to 3.20 GHz. 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. Firstly, 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 Figure 6 where the difference in the IMD2 power of the LDs can be as much as 15 dB. Secondly, 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 add up instead of suppressed. These limitations can be mitigated if a pair of LDs with matched IMD2 characteristics is used and if the lengths 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 are combined into a single optical fiber using a wavelength division multiplexing (WDM) combiner. A different WDM combiner is then used to separate these optical signals to the two photodiodes of the BPD.

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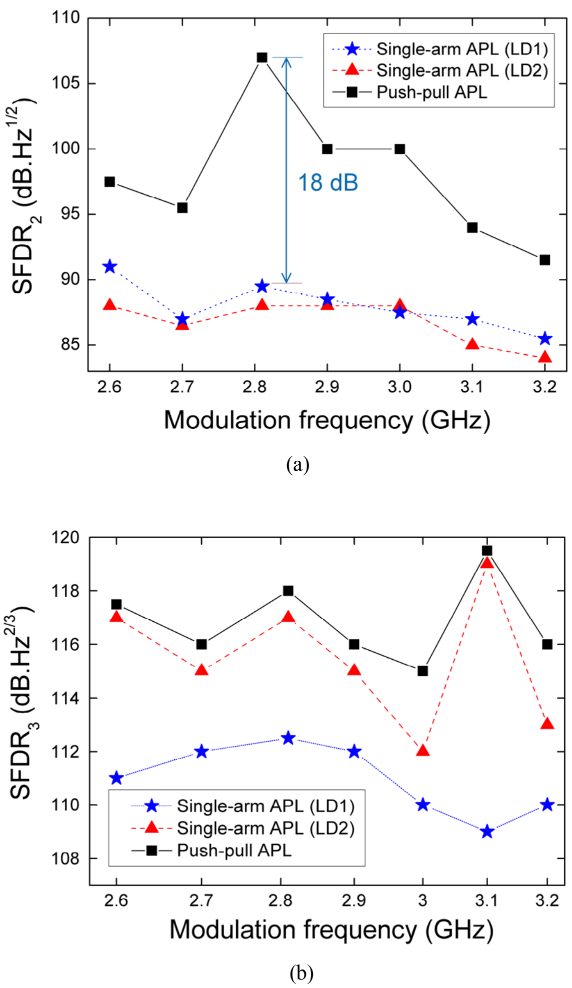

(a)

(b)

Figure 7. The measured $SFDR_2$ (a) and $SFDR_3$ (b) for the push-pull APL and the single-arm APLs as functions of the modulation frequency.

In the frequency range where the IMD2 suppression occurs (as indicated by the grey area in Figure 6), the SFDRs of the push-pull and the single-arm APLs are characterized. As evident from Figure 7 (a), the push-pull APL shows improved $SFDR_2$, over a considerably wide frequency range, relative to the single-arm APLs. $SFDR_2$ improvements ranging from 5 dB to 18 dB have been achieved in a 600 MHz bandwidth, from 2.60 to 3.20 GHz. The maximum $SFDR_2$ improvement of 18 dB is achieved at the modulation frequency of 2.81 GHz. In Figure 7 (b), the measured $SFDR_3$ of the push pull and the individual APLs are depicted. The push-pull APL has a slightly improved $SFDR_3$ relative to the single-arm APL (LD2) with the highest $SFDR_3$. This behavior was also observed in [7]. At the frequency of 2.81 GHz, where the $SFDR_2$ improvement is highest, the $SFDR_2$ and the $SFDR_3$ of the push-pull APL are 108 $dB.Hz^{1/2}$ and 118 $dB.Hz^{2/3}$, respectively. In contrast, the single arm APL with LD2 has a comparable $SFDR_3$ value of 117 $dB.Hz^{2/3}$, but a very limited $SFDR_2$ value of 90 $dB.Hz^{1/2}$.

V. CONCLUSIONS

We have demonstrated experimentally a technique to enhance the multioctave SFDR of a directly modulated LDs APL. The technique is based on a push-pull modulation of LDs and a balanced detection for IMD2 suppression. At a frequency of 2.50 GHz, a very high SFDR of 120 $dB.Hz^{2/3}$ has been achieved. To our knowledge, this is one of the highest values ever achieved with directly modulated LDs. We have extended the measurements in a frequency range of 1.0 up to 4.0 GHz. 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 to 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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