A Broadband High Dynamic Range Analog Photonic Link using Push-Pull Directly-Modulated Semiconductor Lasers

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***Abstract*— We demonstrate an analog photonic link with a high multioctave spurious-free dynamic range (SFDR) of 119 dBHz$^{2/3}$. The link consists of a pair of semiconductor DFB lasers modulated in a push-pull manner and a balanced photodetector. With precise amplitude and phase matchings, a signal enhancement of 4.5 dB and a second-order intermodulation distortion suppression of 40 dB relative to the case of a single arm optical link with one laser can be achieved. To our knowledge, the measured SFDR is one of the highest broadband value ever achieved with directly modulated lasers.**

***Index Terms*— Intermodulation distortion, laser noise, optical modulation, semiconductor lasers**

I. INTRODUCTION

These past few years, there have been numerous research efforts concentrated on the spurious-free dynamic range (SFDR) enhancement of analog photonic links (APLs). Most of the high SFDR APLs that have been reported so far are dominated by externally-modulated links rather than directly modulated ones [1]. This is due to the fact that the former show superior chirp performance compared to the latter, especially for high frequency signals. However, for applications in which a large number of APLs are required, for example in a large-scale phased array antenna for radio astronomy, employing external modulators might become too costly. Hence, using directly modulated lasers (DMLs) is preferred due to their low cost and simplicity. Fortunately, in such a application the APL should only bridge a relatively short length such that the chirp most of the time is not the limiting factor. Nevertheless, the application is very demanding in terms of the SFDR, which is essentially the range of power that can be accommodated by the APL. Hence, APLs with DMLs that can provide sufficiently large SFDR are of importance.

One of the main limitations of APLs with DMLs is the high second-order intermodulation distortion (IMD2) [1]. This prevents the APLs to be implemented in broadband systems in which the signal has a bandwidth of more than one octave. In externally-modulated links with Mach Zehnder modulator (MZM), this limitation is mitigated by means of biasing the MZM in quadrature, which minimizes IMD2 but in turn maximizes the third-order intermodulation (IMD3) [2]. Another way is to use a dual-output MZM [3] in conjunction with a balanced photodetector (BPD). In this paper, we continue the path proposed in [4] with an APL employing a pair of DMLs modulated in a push-pull manner and a BPD for the IMD2 suppression. The principle of operation of the APL is introduced in the second section while the measurement setup and results are presented in the third and fourth sections, respectively. Finally, the paper ends with a conclusion.

II. PRINCIPLE OF OPERATION

The APL archictecture is shown in Fig.1. It consists of a 180° hybrid that supplies antiphase RF signals to a pair of DMLs. In this way, the DMLs 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 modulated optical signals such that upon arriving to the BPD, they have the same amplitude and maintain the 180° phase difference. The BPD simply subtracts the signals of the upper and the lower arms of the APL. In the ideal case of perfect amplitude and phase matchings, the output RF signal will be 6 dB higher compared to the case of a single arm APL (which can be obtained by means of disconnecting one of the optical fibers to the BPD) and the IMD2 at the output will be completely suppressed since the IMD2 components in the upper and the lower arms are in-phase. This suppression allows the APL to have the same SFDR for both single-octave (narrowband) and multioctave (broadband) signals, and is limited by the IMD3.

Unlike in the case of a push-pull modulation with the dual-output MZM where the relative intensity noise (RIN) of the laser source is partly suppressed in the BPD, the noise from the DMLs in our APL adds up incoherently at the output because they are uncorrelated. However, as will be shown later, we have chosen the bias current of our DMLs such that the RIN is already low and the shot noise is dominant. In any case, an SNR enhancement of 3 dB compared to the single arm APL can be expected. In the next section the measurement setup of the APL is presented.

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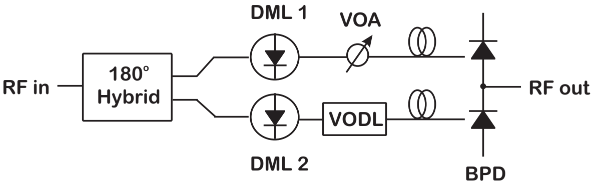

Fig. 1. The proposed APL for broadband SFDR enhancement. DML: directly modulated laser, VOA: variable optical attenuator, VODL: variable optical delay line, BPD: balanced photodetector

III. MEASUREMENT SETUP

A two-tone measurement was carried out to characterize the distortion (and subsequently the SFDR) of the APL. However, due to the unavailability of the 180° hybrid and the VODL during the measurements, the measurement setup of the APL was adjusted to the one shown in Fig.2. An RF splitter and a tunable phase shifter (1-5 GHz frequency range) are used in place of the hybrid and the VODL to perform the push pull modulation and to correct any phase imbalance in the APL. In contrast to the VODL, the phase shifter is strongly frequency dependent and that prevents us to extend our two-tone measurements to a larger frequency range (for example to cover the complete UHF band) without making extensive adjustments in the measurement setting. For this reason, we decided to perform the two-tone test around the modulating frequency of 2.50 GHz which is the highest frequency that can be achieved in the current measurement setting and is limited by the laser diode mounts (ILX Lightwave LDM-4980RF, 2.5 GHz modulation bandwidth) used in the measurements.

We use a network analyzer (Agilent N5230A) and a vector signal generator (Agilent E4438C) to supply the two tones of 2.50 GHz and 2.51 GHz to the DMLs via a 2:1 combiner and a 1:2 splitter. The RF insertion loss of the combiner, splitter and the phase shifter amounts to approximately 8 dB. The DMLs are 1310 nm DFB lasers from Fitel with 20 mW maximum output optical power and 4 GHz modulating bandwidth. The measured threshold currents are 9.5 mA for both lasers. In order to avoid clipping of large modulating signals, the DMLs should be biased around 50 mA, which is roughly half of the difference between the maximum injection current prescribed in the datasheets (100 mA) and the threshold current. Because in the laser characterization (see Section IV) the DML1 has shown higher IMD2 compared to the DML2, the VOA is placed in the upper arm APL to attenuate the optical power and subsequently to match the IMD2 amplitude in both of the arms. It is also possible to equalize these amplitudes with an RF step attenuator instead of the VOA. However, in the measurement setup, finer adjustments can be obtained with the VOA (0.01 dB optical attenuation step) compared to our RF attenuator (1 dB RF attenuation step).

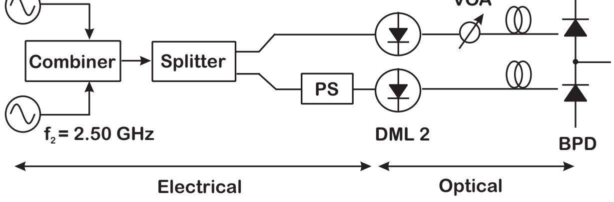

Fig. 2. The measurement setup. The 180° hybrid and the variable optical delay line are replaced by a splitter and an RF tunable phase shifter (PS)

The fundamental, IMD2 and IMD3 powers are measured at the output of the BPD (Discovery Semiconductor DSC-710) with an electrical spectrum analyzer (HP 8593E) at frequencies of 2.50 GHz, 5.01 GHz (2.50 GHz+2.51 GHz) and 2.52 GHz (2×2.51 GHz−2.50 GHz), respectively. For the noise measurements, a low noise amplifier (LNA, Mini Circuits ZRL-2400+) with a gain of 23.2 dB and noise figure of 1.4 dB at the frequency of 2.5 GHz was used to reduce the displayed analyzer noise level (DANL) of the spectrum analyzer. The measurement results are presented in the following section.

IV. MEASUREMENT RESULTS

A. IMD2 and IMD3 in the Single Arm APL

The measured IMD2 and IMD3 powers of the upper and lower (single) arm APLs as functions of the bias currents are shown in Fig.3. As mentioned previously, the DML1 has shown a higher IMD2 power compared to the DML2 (upper part of Fig.3). In order to precisely match the IMD2 amplitudes of the single arm APLs, the VOA is adjusted to 1 dB attenuation. Since the insertion loss of the VOA in our setup amounts to 1.5 dB, the total optical attenuation in the upper arm to achieve IMD2 amplitude matching is 2.5 dB. It is important to mention that this attenuation will sacrifice the link gain in the dual arm APL (subsection B) because the fundamental power in the upper arm APL will also be reduced.

In the lower part of Fig.3, the IMD3 powers as functions of the bias current are shown. Generally, the DMLs show much lower third order nonlinearity compared to the second order one, as expected. However, the DML1 shows considerably larger variations of IMD3 power compared to the DML2. This is due to the amplitude instability (with respect to time) observed in the measured IMD3 of the DML1, which is not observed in the DML2. We have not yet identified the source of this instability, but seemingly this is particular to the DML1 unit. In order to reduce the variation, averaging was done in every IMD3 measurement involving DML1.

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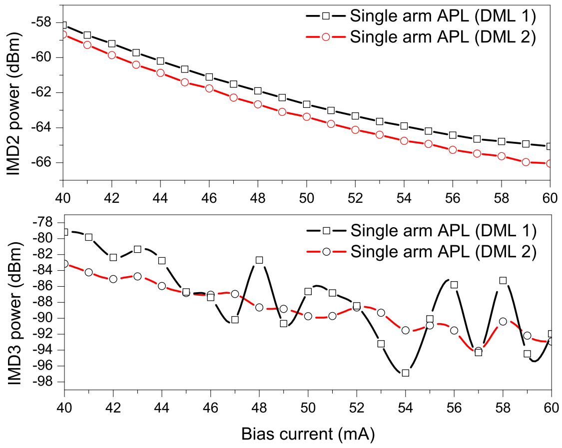

Fig. 3. IMD2 and IMD3 characterizations of the single arm APLs. The input RF power to the link is 1.5 dBm

B. IMD2 Suppression and Signal Enhancement in the Dual Arms APL

For the dual arm APL, the operating bias points for the DML1 and DML2 are chosen to be 51 mA and 52 mA, respectively. We have to mention that this choice is not yet optimized and further investigation is required to determine the optimum bias currents. With precise amplitude and phase matchings, an IMD2 suppression of 40 dB can be achieved at these bias currents, as shown in Fig. 4. As for the fundamental tone, the powers in the upper and lower arm APLs add up coherently as expected (Fig. 5). Note that the fundamental power in the single arm APL with DML1 is lower by 2.5 dB compared to the the one with DML2, making the signal enhancement of the dual arm APL compared to the single arm APL with DML2 amounts to approximately 4.5 dB instead of the theoretical value of 6 dB [5].

The contour plot in Fig 6 represents the IMD2 power as a function of bias current variation of the DMLs. In the measurement, the attenuation of the VOA and the amount of phase shift between the upper and the lower arm of the APL were kept constant. The result shows that the IMD2 suppression is fairly sensitive to the bias current variation. This is attributed to the amplitude variations of the IMD2 with respect to the bias currents, which cannot be corrected with a fixed attenuation.

C. Noise in the APLs

The measured noise power spectral density (PSD) for the upper and the lower arm APLs after the correction of the LNA gain and noise figure are -166.8 dBm/Hz and -164.5 dBm/Hz, respectively. As we mentioned earlier, both APLs at the bias currents beyond 50 mA are shot noise

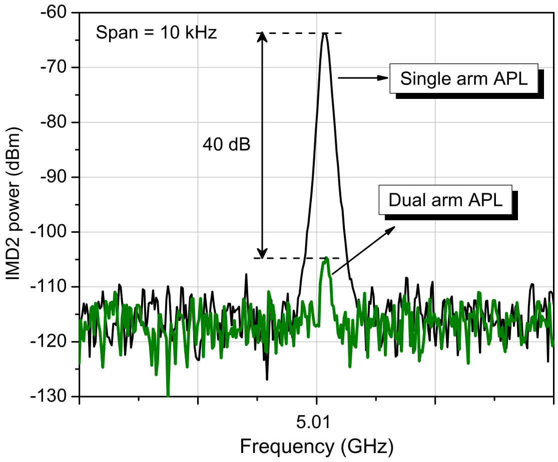

Fig. 4. Suppression of second-order intermodulation distortion. The frequency span is 10 kHz and the input RF power is 1.5 dBm.

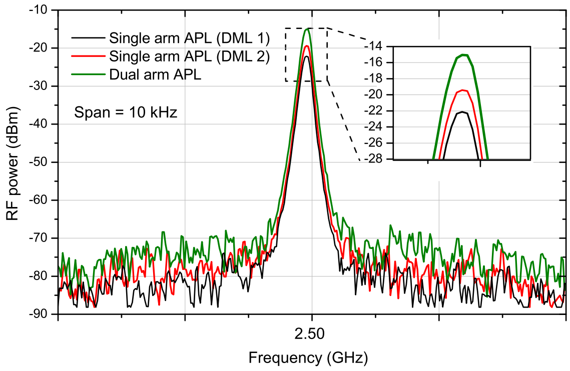

Fig. 5. Coherent addition of the signal power at 2.5 GHz. The frequency span is 10 kHz and the input RF power is 1.5 dBm.

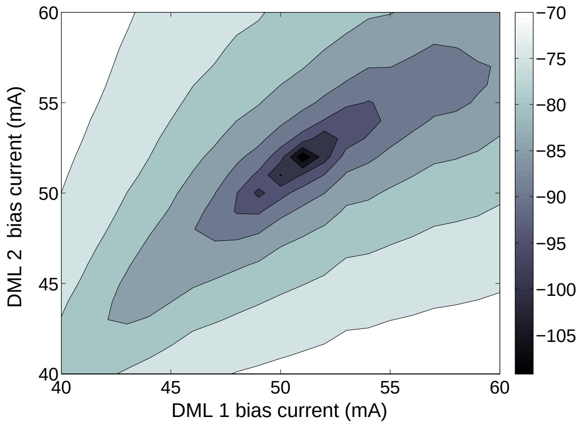

Fig. 6. IMD2 power as a function of the DMLs bias currents. The input RF power is -3.5 dBm.

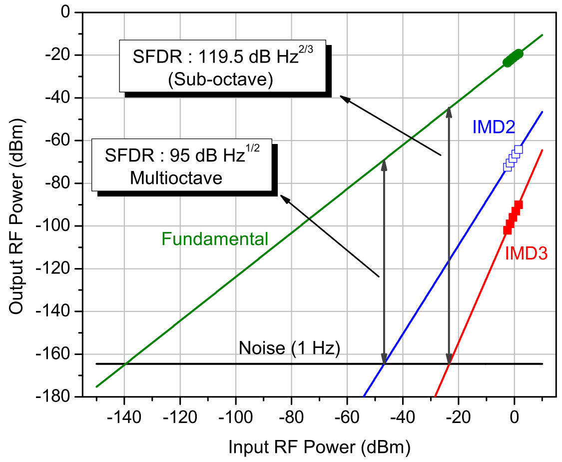

Fig. 7. The measured SFDR for the single arm APL with DML2. The multioctave SFDR is limited by the IMD2.

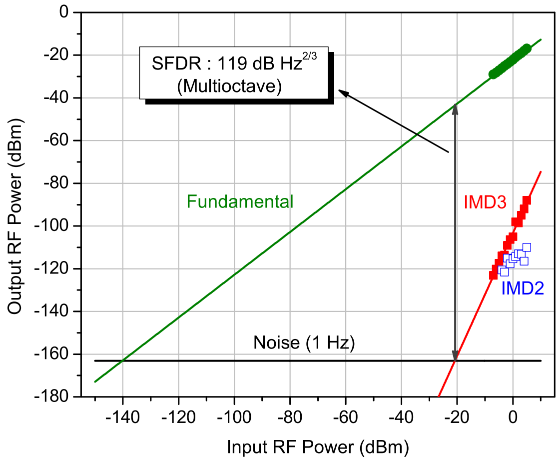

Fig. 8. The measured SFDR for the dual arm APL. The IMD2 is suppressed such that the limiting distortion is IMD3.

limited with the measured RIN values are better than -165 dB/Hz. For the dual arms APL the noise contribution of the upper and the lower arm APLs add up incoherently and PSD amounts to -163 dBm/Hz.

D. SFDR

A widely accepted definition of SFDR of an APL is the output signal-to-noise ratio (SNR) at the input power where the IMD2 or IMD3 power equals to the noise power [6]. For broadband APL, the sub-octave SFDR equals to the multioctave SFDR and is limited by IMD3 rather than by IMD2. In contrast, narrowband APL has a smaller multioctave SFDR (limited by IMD2) compared to the sub-octave SFDR (limited by IMD3). As expected the single arm APL is only suitable for narrowband application since the multioctave SFDR (95 dBHz$^{1/2}$) is much smaller compared to the sub-octave SFDR (119.5 dBHz$^{2/3}$) as shown in Fig.7.

As for the dual arms APL, the IMD2 is largely suppressed and the limiting distortion is IMD3. Although the instability of the IMD3 in the DML1 adds some uncertainties in the SFDR measurement, a broadband SFDR value of 119 dBHz$^{2/3}$ can be obtained, as shown in Fig.8. To our knowledge, this value is among the highest ever reported for multioctave SFDR in directly-modulated links [1]. As a comparison, the regularly cited value as the highest broadband SFDR in such links is 120 dBHz$^{2/3}$ [7], which was shown in an APL with a similar arrangement as our setup but with a lower frequency of 1 GHz [4].

V. CONCLUSION

Measurement results on a potentially low cost, broadband high SFDR APL have been presented. Suppression of second order distortion up to 40 dB and signal power enhancement of 4.5 dB relative to the single arm APL have been achieved. By proper biasing of the lasers, the APL noise is shot noise limited. The multioctave SFDR of 119 dBHz$^{2/3}$ at 2.5 GHz modulating frequency to our knowledge is one of the highest values ever reported for directly-modulated APL. We have shown this high performance APL with commercially available components. The further objective is to improve the APL performance with better DMLs and broadband 180° hybrid and a VODL.

ACKNOWLEDGMENT

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REFERENCES

[1] C. H. Cox, E. I. Ackerman, G. E. Betts and J. L. Prince “Limits and performance of RF-over-fiber links and their impact on device design ,” *IEEE Trans. Microwave Theory & Tech.*, vol. 54, no. 2, pp. 906-920, February 2006.

[2] S. Mathai et al., “Experimental demonstration of a balanced electroabsorption modulated microwave photonic link ,” *IEEE Trans. Microwave Theory & Tech.*, vol. 49, no. 10, pp. 1956-1961, October 2001.

[3] K. J. Williams, L. Nichols and R. Esman “Photodetector nonlinearity limitations on a high dynamic range 3 GHz fiber optic link ,” *J. Lightw. Technol.*, vol. 16, no. 2, pp. 192-199, February 1998.

[4] S. Pappert, C. Sun, R. Orazi, and T. Weiner, “Microwave fiber optic links for shipboard antenna applications”, *Proc. 2000 IEEE Int. Conf. Phased Array Systems and Technology*, pp. 345-348, 2000.

[5] M. S. Islam et al., “Distributed balanced photodetectors for high-performance RF photonic links ,” *IEEE Photon. Tech. Lett.*, vol. 11, no. 4, pp. 457-459, April 1999.

[6] C. Cox, *Analog Optical Links*, Cambridge, UK: Cam,bridge Univ. Press., 2004.

[7] E. I. Ackerman and C. H. Cox, III,“RF fiber-optic link performance,” *IEEE Microwave Magazine*, vol. 2, no. 4 pp. 50-58, December 2001.