Dynamic range improvement of a microwave photonic link based on bi-directional use of a polarization modulator in a Sagnac loop

Wangzhe Li and Jianping Yao[*]

Microwave Photonics Research Laboratory, School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON, K1N 6N5, Canada

[*] *jpyao@eecs.uOttawa.ca*

Abstract: A novel microwave photonic link (MPL) with an improved spurious-free dynamic range (SFDR) based on a bidirectional use of a polarization modulator (PolM) in a Sagnac loop is proposed and demonstrated. The PolM in the loop functions, in conjunction with a polarization controller and a polarization beam combiner, as a Mach Zehnder modulator (MZM), which only modulates the incident light wave along the clockwise direction, leaving the counter-clockwise light wave unmodulated due to the velocity mismatch. Two clockwise intensity-modulated signals along two paths (Path 1 and Path 2) are generated, with one (Path 2) combined with the non-modulated light wave from the counter-clockwise direction to suppress part of the optical carrier. By controlling the power relationship between the two paths, the third-order intermodulation distortion (IMD3) can be fully suppressed, and thus an MPL with improved dynamic range is achieved. A theoretical analysis is presented, which is validated by an experiment. The IMD3 can be suppressed by 50 dB, giving an improvement in SFDR of 16 dB.

OCIS codes: (060.2360) Fiber optics links and subsystems; (060.5625) Radio frequency photonics; (130.4110) Modulators; (350.4010) Microwaves.

References and links

1. C. Cox, *Analog optical links: Theory and Practice* (Cambridge University Press, 2006)
2. J. P. Yao, “Microwave photonics,” J. Lightwave Technol. **27**(3), 314–335 (2009).
3. X. Meng and A. Karim, “Microwave photonic link with carrier suppression for increased dynamic range,” Fiber Int. Opt. **25**(3), 161–174 (2006).
4. A. Agarwal, T. Banwell, P. Toliver, and T. K. Woodward, “Predistortion compensation of nonlinearities in channelized RF photonic links using a dual-port optical modulator,” IEEE Photon. Technol. Lett. **23**(1), 24–26 (2011).
5. T. R. Clark, S. R. O’Connor, and M. L. Dennis, “A phase-modulation I/Q-demodulation microwave-to-digital photonic link,” IEEE Trans. Microw. Theory Tech. **58**(11), 3039–3058 (2010).
6. Y. Shen, B. Hraimel, X. Zhang, G. E. R. Cowan, K. Wu, and T. Liu, “A novel analog broadband RF predistortion circuit to linearize electro-absorption modulators in multiband OFDM radio-over-fiber systems,” J. Lightwave Technol. **58**(11), 3327–3335 (2010).
7. A. Fard, S. Gupta, and B. Jalali, “Digital broadband linearization technique and its application to photonic time-stretch analog-to-digital converter,” Opt. Lett. **36**(7), 1077–1079 (2011).
8. G. Zhang, S. Li, X. Zheng, H. Zhang, B. Zhou, and P. Xiang, “Dynamic range improvement strategy for Mach-Zehnder modulators in microwave/millimeter-wave ROF links,” Opt. Express **20**(15), 17214–17219 (2012).
9. G. Zhang, X. Zheng, S. Li, H. Zhang, and B. Zhou, “Postcompensation for nonlinearity of Mach-Zehnder modulator in radio-over-fiber system based on second-order optical sideband processing,” Opt. Lett. **37**(5), 806–808 (2012).
10. R. D. Esman and K. J. Williams, “Wideband efficiency improvement of fiber optic systems by carrier subtraction,” IEEE Photon. Technol. Lett. **7**(2), 218–220 (1995).
11. J. D. Bull, T. E. Darcie, J. Zhang, H. Kato, and N. A. F. Jaeger, “Broadband class-AB microwave-photonic link using polarization modulation,” IEEE Photon. Technol. Lett. **18**(9), 1073–1075 (2006).
12. T. E. Darcie, A. Moye, P. F. Driessen, J. D. Bull, H. Kato, and N. A. F. Jaeger, “Noise reduction in class-AB microwave-photonic links,” IEEE Int. Topical Meeting Microw. Photon. (2005) 329–332.

#188628 - $15.00 USD Received 10 Apr 2013; revised 10 Jun 2013; accepted 10 Jun 2013; published 24 Jun 2013

13. S. K. Kim, W. Liu, Q. Pei, L. R. Dalton, and H. R. Fetterman, “Nonlinear intermodulation distortion suppression in coherent analog fiber optic link using electro-optic polymeric dual parallel Mach-Zehnder modulator,” Opt. Express **19**(8), 7865–7871 (2011).
14. M. Huang, J. Fu, and S. Pan, “Linearized analog photonic links based on a dual-parallel polarization modulator,” Opt. Lett. **37**(11), 1823–1825 (2012).
15. X. Chen, W. Li, and J. P. Yao, “Microwave photonic link with improved dynamic range using a polarization modulator,” IEEE Photon. Technol. Lett. (Submitted to).
16. J. D. Bull, N. A. F. Jaeger, H. Kato, M. Fairburn, A. Reid, and P. Ghanipour, “40 GHz electro-optic polarization modulator for fiber optic communications systems,” Proc. SPIE **5577**, 133–143 (2004).
17. W. Li and J. P. Yao, “Microwave and terahertz generation based on photonically assisted microwave frequency twelvetupling with large tunability,” IEEE Photon. J. **2**(6), 954–959 (2010).
18. D. Marpaung, C. Roeloffzen, A. Leinse, and M. Hoekman, “A photonic chip based frequency discriminator for a high performance microwave photonic link,” Opt. Express **18**(26), 27359–27370 (2010).

1. Introduction

Microwave photonic links (MPLs) with wide bandwidth, low loss and immunity to electromagnetic interference [1, 2] have been intensively studied for various applications such as wireless communications, radars, antenna remoting, and warfare systems. These applications require ever-increasing bandwidth and dynamic range, and are typically realized by an MPL based on external modulation [3–5]. However, the demand for high spurious-free dynamic range (SFDR) of many of these applications present a major obstacle to fully realizing the benefits of an MPL due to the nonlinear transfer function of an electrical-to-optical modulator and the excessive optical power at the carrier frequency. Many electrical and optical approaches to enhancing the SFDR have been proposed. For example, in the electrical domain, by studying the nonlinearity of an MPL, a pre-distortion [6] or post-processing [7] circuit is employed to modify a microwave signal applied to the modulator or a recovered microwave signal at the output of a photodetector, leading to the correction of the nonlinear distortion in the MPL. An improvement in SFDR of more than 10 dB has been demonstrated. The compensation of the nonlinearity of an MPL can also be implemented in the optical domain [8, 9] by using an optical pulse shaper, which serves as an optical processor to modify the phase and amplitude of the high-order sidebands of the modulated light wave. Although an increase in SFDR as large as 20 dB has been demonstrated, the system incorporating the optical process is very complicated and expensive. Other solutions to improve the dynamic range in the optical domain have been also proposed. Carrier suppression technique [3, 10] can increase the SFDR by reducing the detected relative intensity noise. The implementation is simple, but an external optical filter is usually required. In analogy to a class-AB electronic amplifier, a class-AB MPL [11, 12] using two modulators and two photodetectors has been proposed. The two modulators are operating complementarily which is achieved by properly biasing the modulators to shift their transfer functions such that a new transfer function that is capable of reducing the shot noise leading to an increase in the SFDR is obtained. The SFDR of an MPL can also be increased based on a pair of parallel modulators that have non-identical modulation indices [13, 14]. By controlling the optical powers going through the modulators, the third-order intermodulation distortions (IMD3) introduced by two paralleled modulators can be fully cancelled, leading to an increase in SFDR of about 15 dB [14]. However, the system consists of two laser sources, two modulators, and two photodetectors, which is complicated and would significantly increase the system cost. Moreover, additional noise could be introduced due to the use of additional active devices, which would degrade the performance of the MPL. Recently, we have proposed and demonstrated an MPL using a single PolM. The PolM functions as two equivalent Mach-Zendhre modulators (MZMs) operating at the opposite slopes. By using a phase-shifted fiber Bragg grating (PS-FBG) to suppress the optical carrier of one channel and splitting the optical powers into the two channels with identical power, the IMD3 was completely suppressed. The proposed MPL was experimentally demonstrated. An improvement in SFDR of 10 dB was experimentally achieved [15]. The major limitation of the approach is the use of a PS-FBG, which is sensitive to environmental changes, making the MPL have poor stability. In addition, the notch with a finite width also removes the spectral

#188628 - $15.00 USD Received 10 Apr 2013; revised 10 Jun 2013; accepted 10 Jun 2013; published 24 Jun 2013

components close to the optical carrier from the sidebands, causing that the IMD3 cannot be completely removed in theory, and the increase of the SFDR is theoretically and practically limited to 10 dB.

In this paper, an MPL with an enhanced SFDR is proposed based on a bidirectional use of a single polarization modulator (PolM) in a Sagnac loop. Since no optical filter is used, the MPL has better stability. The PolM is a traveling-wave modulator which is designed to have effective modulation for one direction due to the match of velocities of the light wave and the microwave along that direction. For the other direction, due to the velocity mismatch, the modulation is very weak and can be negligible. In the Sagnac loop, although the light waves in both clockwise and counter-clockwise directions go through the PolM, the PolM only modulates the light wave traveling along one direction (say, the clockwise direction), leaving the light wave in the opposite direction (say, the counter-clockwise direction) unmodulated. In the Sagnac loop, two clockwise intensity-modulated signals along two paths (Path 1 and Path 2) are generated, with one (Path 2) combined with the unmodulated light wave from the counter-clockwise direction to suppress part of the optical carrier. By controlling the power relationship of the two paths, the IMD3 can be suppressed, thus an MPL with improved dynamic range is achieved. A theoretical analysis is presented, which is validated by an experiment. The IMD3 can be suppressed by 50 dB, giving an improvement in SFDR of about 16 dB. For a noise floor of –166 dBm/Hz, an SFDR of 121 dB·Hz$^{2/3}$ can be achieved.

2. Principle

The schematic of the proposed MPL with an improved SFDR is shown in Fig. 1. A continuous-wave (CW) light wave from a laser diode (LD) is sent to a Sagnac loop via a polarization controller (PC1) and a 2 × 2 optical coupler (C1). A PolM, a PC and another optical coupler (C2) are included in the Sagnac loop. Via C2, only a portion of the clockwise light wave is routed out of the Sagnac loop and sent to a polarization beam combiner (PBC) via a PC (PC2) (Path 1); while the remaining portion of the clockwise light wave and the counter-clockwise light wave are routed out of the loop at port 2 of C1, and also sent to the PBC via a PC (PC3) (Path 2).

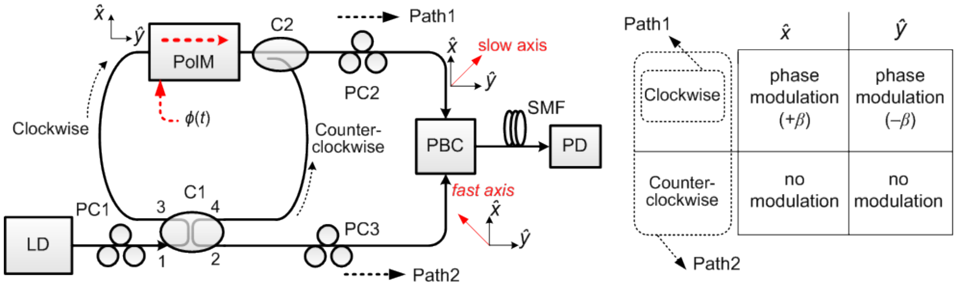

Fig. 1. Schematic of the proposed microwave photonic link based on a bidirectional use of a PolM in a Sagnac loop.

A PolM is a special phase modulator that supports phase modulation with opposite modulation indices along the two orthogonal principal axes of the PolM, $\hat{\boldsymbol{x}}$ and $\hat{\boldsymbol{y}}$ [16]. The two principal axes of the PolM are analogous to the two physically separated arms in a conventional MZM, thus by a joint use of a PC and a PBC to project the light waves along $\hat{\boldsymbol{x}}$ and $\hat{\boldsymbol{y}}$ axes to an identical polarization direction for interference, an equivalent MZM can be achieved [17]. Therefore, the light waves traveling in Path 1 and Path 2 will become intensity-modulated at the output of the PBC, and orthogonally polarization-multiplexed.

By adjusting PC1 to make the polarization direction of the incident clockwise and counter-clockwise light waves at an angle of 45° relative to axis $\hat{\boldsymbol{x}}$ and $\hat{\boldsymbol{y}}$, as shown in Fig.

1, we have, 1) along the clockwise direction, two phase-modulated light waves with identical amplitudes, but opposite phase modulation indices are generated; 2) along the counter-clockwise direction, two non-phase-modulated light waves with identical amplitudes are generated. The non-phase modulation along the counter-clockwise direction is due to the fact that the PolM is a traveling wave modulator, when it is used in a reverse direction, the velocity mismatch between the clockwise microwave signal and the counter-clockwise light wave would make the counter-clockwise light wave experience very weak phase modulation, which can be ignored.

Therefore, if in Path 1, PC2 is adjusted to ensure the two orthogonally polarized light wave to be both oriented at an angle of 45° to one principal axis (say, the slow axis) of the PBC, while in Path 2, PC3 is adjusted to ensure the two orthogonally polarized light waves to be oriented, respectively, at an angle of 45° and 135° to the other principal axis (say, the fast axis) of the PBC, the orthogonally polarization multiplexed light waves at the output of the PBC can be expressed as

$$\begin{bmatrix} E_s \\ E_f \end{bmatrix} = \begin{bmatrix} E_1\left\{\cos\left[\omega_o t+\beta\phi(t)/2-\theta\right]+\cos\left[\omega_o t-\beta\phi(t)/2\right]\right\} \\ E_2\left\{\cos\left[\omega_o t+\beta\phi(t)/2-\theta\right]-\cos\left[\omega_o t-\beta\phi(t)/2\right]+\cos\left(\omega_o t-\theta\right)-\cos\left(\omega_o t\right)\right\} \end{bmatrix} \quad (1)$$

where E_s and E_f are the electrical fields of the light waves along the slow and the fast axes of the PBC, E_1 and E_2 are the corresponding amplitudes, ω_o is the angular frequencies of the optical carrier, $\phi(t)$ is the microwave signal applied to the PolM, β is the phase modulation index, and θ is the phase difference between the light waves along two axes of the PolM, which could also be introduced by PC1. Given $\theta = \pi/2$, the PolM-based intensity modulator is biased at the quadrature point. When the output of the PBC is sent to the PD for square-law detection, the detected microwave components can be expressed as

$$\begin{aligned} I &= ac\left[\Re\left(\left|E_s\right|^2+\left|E_f\right|^2\right)\right]=\Re P_s\cos\left[\beta\phi(t)-\pi/2\right] \\ &+\Re P_f\left\{-\cos\left[\beta\phi(t)-\pi/2\right]-\sqrt{2}\sin\left[\beta\phi(t)/2-\pi/4\right]+\sqrt{2}\sin\left[-\beta\phi(t)/2+\pi/4\right]\right\} \\ &=\Re P_s\sin\left[\beta\phi(t)\right]+\Re P_f\left\{-\sin\left[\beta\phi(t)\right]-2\sqrt{2}\sin\left[\beta\phi(t)/2-\pi/4\right]\right\} \\ &=\Re P_s\sin\left[\beta\phi(t)\right]+\Re P_f\left\{-\sin\left[\beta\phi(t)\right]-2\sin\left[\beta\phi(t)/2\right]+2\cos\left[\beta\phi(t)/2\right]\right\} \end{aligned} \quad (2)$$

where $\Re$ is the responsivity of the PD, P_s and P_f are the optical powers along Path 1 and Path 2, and $ac[\ ]$ represents the ac term. We can simplify Eq. (2) by expanding the sine function in a Taylor series:

$$\begin{aligned} I &\approx \Re P_s\left[\beta\phi(t)-\beta^3\phi^3(t)/6\right]-\Re P_f\left\{\beta\phi(t)-\beta^3\phi^3(t)/6+2\left[\beta\phi(t)/2-\beta^3\phi^3(t)/48\right]\right\} \\ &+2\Re P_f\left[1-\beta^2\phi^2(t)/8\right] \\ &=\Re\left(P_s-2P_f\right)\beta\phi(t)-\Re\left(P_s-5P_f/4\right)\beta^3\phi^3(t)/6+2\Re P_f\left[1-\beta^2\phi^2(t)/8\right] \end{aligned} \quad (3)$$

From (3), we can clearly see that given the input microwave signal $\phi(t)$ to be a two-tone microwave signal, the first term on the right-hand side represents the recovered fundamental two-tone microwave signal, the second term on the right-hand side would produce the IMD3 components and the third term would generate second-order distortions. Among these distortions, the IMD3 components are considered most troublesome in an MPL for the IMD3 components usually fall at a frequency near the fundamental frequencies, and are in the pass band of the MPL. To increase the SFDR of the MPL, the IMD3 has to be suppressed; therefore, the coefficient of $\beta^3\phi^3(t)$ in the second term on the right-hand side should be zero,

$$P_s-5P_f/4=0 \quad (4)$$

Equation (4) can be easily satisfied by adjusting the optical power along either Path 1 or Path 2. Note that while the IMD3 is reduced, it comes at the cost of adding a 2nd-order harmonic term.

Based on Eq. (3) and Eq. (4), we can compare the powers of the recovered fundamental microwave signals in two cases: 1) Path 1 is connected and Path 2 is not, which represents a conventional MPL, and 2) both Path 1 and Path 2 are connected and Eq. (4) is satisfied, which results in the suppression of the IMD3 and the improvement of the SFDR. The power difference in the two cases can be given by

$$20\log_{10}\left|\frac{P_s}{P_s-2P_f}\right| = 20\log_{10}\left|\frac{P_s}{P_s-2\times 4P_s/5}\right| = 20\log_{10}\left|\frac{5}{3}\right| \approx 4.4\text{dB} \qquad (5)$$

Equation (5) indicates that when Path 2 is connected to realize IMD3 suppression, the power of the recovered fundamental microwave signal would be reduced by 4.4 dB.

3. Experimental results and discussion

An experiment based on the schematic shown in Fig. 1 is conducted. A CW light wave at 1550 nm from a tunable laser source (Anritsu, MG9638A) is sent to the Sagnac loop. The PolM (Versawave) inside the loop has a bandwidth of 40 GHz and a half-wave voltage of about 5.5 V for a modulation frequency at around 5 GHz. In the experiment, an additional PC (not shown in Fig. 1) is placed between C1 and C2 in the Sagnac loop to facilitate the adjustment of the polarization states of the light wave inside the loop. The lengths of Path 1 and Path 2 are set to be identical. The optical power at the output of the PBC is about −8 dBm, which is amplified to 10 dBm before sending to the PD (u^2t, XPDV2150R). The PD has a measured responsivity of 0.45 A/W and a bandwidth of 50 GHz.

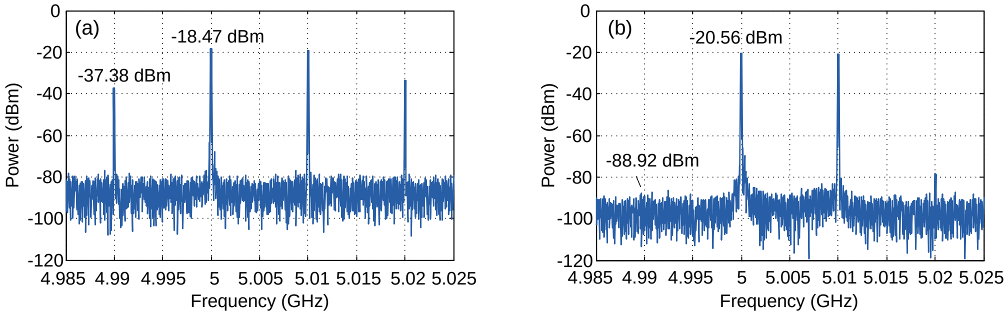

Fig. 2. Electrical spectra of the RF signal at the output of the PD when a two-tone RF signal is applied to the PolM. (a) Only Path 1 is connected, and (b) both Path 1 and Path 2 are connected. RBW: 30 kHz.

To investigate the suppression of the IMD3, a RF signal with two tones at 5 GHz and 5.01 GHz from a vector network analyzer (Agilent, E8364A) and a microwave source (Agilent E8254A), respectively, is applied to the PolM via the RF port. The electrical spectra of the signal at the output of the PD are measured by an electrical spectrum analyzer (ESA, Agilent E4448A) in two cases: 1) only Path 1 is connected, as shown in Fig. 2(a); 2) both Path 1 and Path 2 are connected, as shown in Fig. 2(b). In the first case, the PolM functions, in conjunction with PC2 and the PBS, as an MZM biased at the quadrature point, and Path 1 can be considered as a conventional MPL based on an MZM. Strong IMD3 components can be observed due to the nonlinearity of the MZM. In the second case, the optical power in Path 2 is adjusted to satisfy (3) to suppress the IMD3. As can be seen from the Fig. 2, the IMD3 components can be suppressed as large as 50 dB. In addition, comparing with the first case, the power of the fundamental microwave signal in the second case is decreased by 2.09 dB. which agrees well with theoretical calculation. Note that the RF gain of the link for Case 1 is about −28 dB, which is lower than the theoretical value of −23 dB. The lower link gain is mainly due to the loss of the microwave cable and the insertion loss when the light wave is sent to the PD.

In the experiment, due to the low directivity of C1 and C2 used in the demonstration and undesired fiber facet reflections in the Sagnac loop, a portion of the incident optical carrier is coupled into Path 2 via C1 and a portion of the counter-clockwise light wave is coupled into Path 1 via C2, which cause undesired optical interference, resulting in an unstable suppression of the IMD3, especially when the suppression ratio is greater than 50. In the experiment, a stable IMD3 suppression for a suppression ratio of 35 dB or less is always maintained.

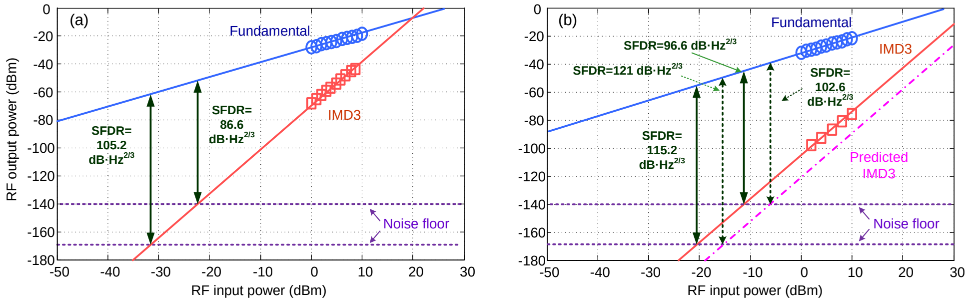

Fig. 3. Measured RF powers of the fundamental signal and IMD3 at the output of the PD when a two-tone signal is applied to the PolM. (a) Only Path 1 is connected, and (b) both Path 1 and Path 2 are connected.

Then, the measurements of the output microwave powers of the fundamental signals and the powers of the IMD3 in two cases are performed and the results are shown in Fig. 3. Given a noise floor of −140 dBm/Hz which is the noise floor the ESA used in our experiment, the measured SFDRs are 86.6 $\mathrm{dB \cdot Hz^{2/3}}$ and 96.6 $\mathrm{dB \cdot Hz^{2/3}}$ for Case 1 and Case 2, respectively. An improvement in the SFDR of 10 dB is achieved. It should be noticed that if a higher performance optical couplers with higher directivity used, stable 50-dB IMD3 suppression would be maintained, and the improvement of the SFDR can be as large as about 16 dB. In such a case, a predicted IMD3 curve (dot-dash line) is added in Fig. 3(b), and the predicted SFDR would be increased to 102.6 $\mathrm{dB \cdot Hz^{2/3}}$.

In the experiment, the noise floor of −140 dBm/Hz is limited by the ESA. For an MPL, the noise floor can be controlled as low as −166 dBm/Hz [18], thus the SFDR can be 121 $\mathrm{dB \cdot Hz^{2/3}}$.

4. Conclusion

A novel MPL with an improved SFDR was proposed and demonstrated by a bi-directional use of a PolM in a Sagnac loop. Thanks to the direction-dependent modulation of the PolM in the Sagnac loop, two intensity-modulated light waves with different modulation indices were achieved by jointly using the PolM, PCs and a PBC. By simply controlling the power of one intensity-modulated light wave, the IMD3 components could be completely suppressed. A theoretical analysis was presented which was verified by an experiment. An improvement of the SFDR of 10 dB was demonstrated. A further improvement up to 16 dB with an SFDR of 121 $\mathrm{dB \cdot Hz^{2/3}}$ could be achieved if the noise floor of the link is controlled to be −166 dBm/Hz.

Acknowledgments

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Strategic Grant Project program.