On-chip programmable microwave photonic filter with an integrated optical carrier processor

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Abstract: We demonstrate a programmable microwave photonic bandpass filter with a rectangular frequency response and a reconfigurable spectral resolution. We achieved these features through dual-sidebands processing of a phase modulated signal using a network of four optical ring resonators in a low-loss silicon nitride (Si3N4) circuit. Furthermore, we integrate a pair of optical ring resonators in the same circuit to precisely control the amplitude and phase of the optical carrier to enhance the noise performance of the filter. We achieved filtering with a tunable bandwidth from 2 to 7 GHz with optical carrier suppression up to 6 dB, a maximum RF gain of -10 dB, and a minimum noise figure of 27 dB. These experiments are expected to provide a feasible design to approach fully integrated microwave photonic filters with improved link gain and reduced noise figure.

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1. Introduction

Integrated microwave photonics (MWP) is an emerging field where photonic components manipulate radio frequency (RF) signals with the incorporation of photonic integrated circuits (PICs) in microwave photonic system [1], offers multiple advantages including massive footprint reduction as well as enhance functionality, flexibility and performance, making them more comparable to RF circuits and important for RF front end application. By having these benefits in integrated microwave photonic system, it is important to find a way to combine reconfigurable microwave photonic functionality with noise performance enhancement technique for the broadband and real-time analog signal processing.

Recently, an integrated microwave photonic filter, as an analog signal processing with fully optimized RF performance is obtained with advanced notch filtering functions using low-biasing Mach-Zehnder modulator (MZM) as photonic link optimization technique to achieve low noise figure [NF] [2]. Low-biasing MZM is a noise figure optimization technique that reduces the photocurrent associated with optical noise faster than the RF link gain ($\sin^2 \varphi$) when the MZM bias point is moved from quadrature bias point ($\varphi_{\text{bias}} = \pi/2$) towards null bias point ($\varphi_{\text{bias}} = 0$). It is also important to do the same approach for bandpass filter functions. Such a filter has been researched using various integrated photonic devices, such as optical ring resonators [3,4] and stimulated Brillouin scattering (SBS) [5,6]. In a combination of MZM and optical ring resonator-based system, a rather complex structures are needed to create bandpass filter [7,8]. Moreover, typical MZM suffers from DC bias drift issue, causes slow drift of the optimum bias point for high slope efficiency in analog photonic link [9]. Here, a combination of phase modulator (PM) and all-pass optical ring resonator is used to build the bandpass filter in a simpler, more compact and DC bias drift free system. But the use of PM prevents the advantages of low-biasing operation used readily available in MZM-based systems. To overcome this limitation, an optical carrier suppression technique implemented using external optical filters were used to emulate low biasing [10,11]. In views of integrated MWP systems, it is important to integrate this optical carrier filter with reconfigurable MWP filters in the same circuit, which is the key to achieve hardware-compressed highly integrated filters. Recently, the research of bandpass
filter with carrier suppression combination has been published \[12\]. Nevertheless, the limit of ring-based carrier suppression technique has not been explored to date, nor its combination with more advanced bandpass filtering functions.

In this work, we report and demonstrated experimentally an MWP bandpass filter with a rectangular frequency response and a reconfigurable spectral resolution combined with an optical carrier processor to enhance the noise performance, all integrated on a silicon nitride photonic chip. This bandpass filter was created using dual-sideband processing of phase-modulated signal \[13,14\] while the optical carrier processing was aimed to gain and noise figure enhancement through optimization of the detected optical power. With this approach, we demonstrate a square-shaped bandpass filter with 2-7 GHz tunable bandwidths, an RF gain of -10 dB, and a minimum noise figure (NF) of 27 dB. Further, we provide a comprehensive simulation model to describe the frequency response of the filter with complete RF-photonic link parameters simultaneously. Finally, we analyze the noise performance improvement technique using ring-based optical carrier suppression and compare it with conventional low-biased Mach-Zehnder modulator (MZM).

2. Filter operating principle and system modelling

The operation principle of the proposed microwave photonic bandpass filter is illustrated in Fig. 1. The input RF signal was converted into the optical domain using a phase modulator (PM) creating a signal with identical-amplitude sidebands that are out-of-phase. The PM signal was then processed using a network of ring resonators. There were two key signal processing steps implemented by this ring network: (1) bandpass filtering and (2) optical carrier suppression.

Fig. 1. The principle and experimental setup of the proposed on-chip programmable bandpass filter with integrated optical carrier suppression. Four ring resonators were used to form the square-shaped filter passband. Two more ring resonators were used to partially suppress the optical carrier to emulate low-biasing technique. An optical amplifier (EDFA) was then used to compensate the carrier suppression. The result was a square-shaped bandpass filter with improved noise figure; RF: radio frequency, EDFA: erbium-doped-fiber-amplifier, PC: polarization controller, OC: over-coupling, UC: under-coupling, PD: photodetector.

For creating the square-shaped bandpass filter, we used the resonances of four optical ring resonators operating at the over-coupling (OC) states. These resonances were positioned asymmetrically with respect to the optical carrier \((f_1 \neq f_2 \neq f_3 \neq f_4)\) to control the amplitude and phase of the PM sidebands essentially leading to phase modulation to intensity modulation (PM to IM) conversion \[13\]. Due to OC state in the rings, a \(\pi\) phase shift is introduced at the desired notch frequency, creating constructive interference between mixing product of optical carrier and two sidebands, forming a strong RF passband at \(\omega_{RF}\) with a square shape and a flat top filter response.
Further, we implemented optical carrier suppression through a couple of ring resonators operating at the under-coupling (UC) states. The carrier suppression was used to limit the DC optical power to the photodetector. At the same time, we used optical amplification to boost the strength of the optical sidebands. This combination leads to enhancement of the link gain and noise figure without saturation of the photodetector current, essentially emulating low biasing in the phase modulated system.

We proceed with describing the modelling of the entire MWP filter system. The optical field of the phase modulated signal, considering small signal modulation can be written as

$$E_{pm}(t) = \sqrt{P_i} e^{i\omega_{RF}t} \sum_{n=-1}^{\infty} J_n(m) e^{i\phi_n}$$

where $\omega_c$ and $\omega_{RF}$ is the angular frequency of the optical carrier and input RF signal; $P_i$ is the input optical power, $J_n$ is the $n$-th order Bessel function of the first kind, $m = \pi V_{RF}/V_{RF}$ is the modulation index of PM, $V_{RF}$ is the input RF signal voltage, $V_{RF}$ is the RF half-wave voltage of the PM.

The output signal of cascaded ring resonators for our MWP bandpass filter can be expressed as

$$E_p(t) = \sqrt{P_i} e^{i\omega_{RF}t} (\alpha J_0(m) e^{i\theta_\alpha} + \beta J_1(m) e^{i\omega_{RF}t + \gamma \theta_\gamma} - \gamma J_1(m) e^{-i\omega_{RF}t + \gamma \theta_\gamma})$$

where

$$\alpha = T_1(\omega_c) T_2(\omega_c)$$

$$\theta_\alpha = \theta_1(\omega_c) + \theta_2(\omega_c)$$

$$\beta = T_3(\omega_c + \omega_{RF}) T_4(\omega_c + \omega_{RF})$$

$$\theta_\beta = \theta_3(\omega_c + \omega_{RF}) + \theta_4(\omega_c + \omega_{RF})$$

$$\gamma = T_5(\omega_c - \omega_{RF}) T_6(\omega_c - \omega_{RF})$$

$$\theta_\gamma = \theta_5(\omega_c - \omega_{RF}) + \theta_6(\omega_c - \omega_{RF})$$

Here, the amplitude response $T_k(\omega)$ and phase response $\theta_k(\omega)$ of the $k$th optical ring resonator are given by [15]

$$T_k(\omega) e^{i\theta_k(\omega)} = \frac{a_k - c_k e^{-i\theta_k(\omega)}}{1 - a_k c_k e^{i\theta_k(\omega)}} e^{\pi i \theta_k(\omega)}$$

$$k = 1, 2, \ldots, 6$$

where $c_k$, $\theta_k$, and $a_k$ are self-coupling coefficient, round-trip phase, and single-pass amplitude of the optical ring resonator, respectively.

The optical carrier suppression in Eq. (2) is expressed by the factor $\alpha$, which is dictated by the multiplication of the transmission factors of two ring resonators. We compensate the optical carrier suppression by re-amplification using the gain from an erbium-doped fiber amplifier (EDFA). This re-amplification was done parametrically, such that the DC optical power impinging on the photodetector is constant at various carrier suppression levels. The key concept here is: while carrier suppression is only reducing the DC optical power, the gain of the EDFA is broadband, and will lead to amplification of all frequency components, which include the two RF sidebands. The net result of the combined carrier suppression and parametric amplification are enhanced link gain of the filter with increasing carrier suppression levels.

The photocurrent and RF power at the output of the photodetector can be described as

$$I(t) = R_{PD} P_{det}(t) = R_{PD} E_p(t) E_p^*(t)$$

$$\propto R_{PD} P_i [B_1 + B_2 - B_3]$$

$$P_{RF} = (R_{PD} P_i G_{EDFA} [B_2 - B_3])^2 R_L$$

where

$$B_1 = a^2 J_0^2(m) + (\beta^2 + \gamma^2)J_1^2(m)$$

$$\Delta \theta_1 = \theta_\alpha - \theta_\beta$$

$$B_2 = 2\alpha \beta J_0(m) J_1(m) \cos(\omega_{RF} t - \Delta \theta_1)$$

$$\Delta \theta_2 = \theta_\alpha - \theta_\gamma$$

$$B_3 = 2\alpha \gamma J_0(m) J_1(m) \cos(\omega_{RF} t - \Delta \theta_2)$$

$$\Delta \theta_3 = \theta_\alpha - \theta_\delta$$
with $R_{PD}$, $R_L$, and $G_{EDFA}$ are the responsivity of the photodetector, load resistance, and gain of the EDFA.

Based on the model described earlier, we simulate the response of the programmable MWP bandpass filter with tunable bandwidth using parameters as summarized in Table 1.

| Symbol | Parameter                      | Value    |
|--------|--------------------------------|----------|
| $P_i$  | input optical power           | 18 dBm   |
| $P_{RF_i}$ | input RF power               | -3 dBm  |
| $L_{pm}$ | PM losses                    | 3 dB     |
| $L_{RR}$ | fiber-to-fiber insertion losses | 8.5 dB  |
| $L_{RF_c}$ | Coaxial / RF cable losses    | 2 dB     |
| $G_{EDFA}$ | EDFA gain                  | 3 dB     |
| $V_{RF}$ | input RF signal voltage      | 0.2 V    |
| $V_{R,RF}$ | RF half-wave voltage        | 5 V      |
| $R_{PD}$ | Photodetector responsivity   | 0.6 A/W  |

Here, we synthesize the filter with rectangular spectral resolution, aiming flat top and radical transition between passband and stopband. We utilize resonance from four optical ring resonators to realize the rectangular filter with optical carrier placed at the center of each two resonances frequency. Then, by shifting the ring resonance simultaneously with respect to optical carrier, the central frequency and bandwidth of each phase difference term can be adjusted, and the formed bandpass filter can be modified correspondingly.

3. Experiments and results

3.1. Reconfigurable MWP bandpass filter

The experimental setup of on-chip programmable bandpass filter is depicted in Fig. 1. An optical carrier from a low relative-intensity-noise (RIN) laser (Pure Photonics PPCL550) at 1550 nm is phase modulated using a phase modulator (EOSpace 20 GHz) with optical insertion losses of 3 dB. The PM is driven by an RF signal from a vector network analyzer (VNA, Keysight P9375A) with RF power level at -3 dBm. The output of PM was then sent to a 2 W erbium-doped fiber amplifier (EDFA, Amonics) before being injected into a programmable silicon nitride chip (LioniX International) fabricated using the low-loss TriPleX ($\text{Si}_3\text{N}_4/\text{SiO}_2$) technology [16]. The chip has fiber-to-fiber insertion losses of 8.5 dB and the propagation loss of the optical waveguide is 0.15 dB/cm. The circuit consists of six optical ring resonators coupled to one bus waveguide in series. Each optical ring resonator has a free spectral range (FSR) of 25 GHz and can be tuned through thermo-optic tuning using chromium heaters. The heaters were supplied from voltage source and can be programmed with heater controller in computer. The processed optical signal is sent to a matched photodetector (APIC 40GHz Photodetector). For all measurements, the detected optical power in photodetector remained constant at 10 dBm.

Figure 2 shows the simulation and measurement results of integrated microwave photonic bandpass filter responses at central frequency of 5 GHz based on the principle illustrated in Fig. 1. The bandwidth tuning range is around 6 GHz with passband suppression of 20 dB. It should be noted that the passband gain of the filter was measured to be -16 dB due to the losses introduced at RF-to-optics and optics-to-RF conversion.

We then implemented the optical carrier suppression using two ring resonators. The maximum suppression we can impart using the rings was 6 dB, as depicted in Fig. 3, as expected from Eq. (5), 6 dB suppression of the carrier will lead to 6 dB reduction of the RF link gain (dashed
blue trace in Fig. 3). If we now implement compensation of the suppression via broadband parametric amplification using an EDFA, where the gain of EDFA is tuned to retrieve the optical power level lost by the carrier suppression, we obtain that now the RF link gain is enhanced by 6 dB compared to the case with no carrier suppression. This means that we achieve link gain advantage without increasing DC photocurrent, which is essentially the benefit that typically one gets from traditional low-biased MZM intensity modulated links.

We plot the measured RF link gain with EDFA compensation together with the calculated link gain expressed in Eq. (5). As comparison, we plot the uncompensated link gain, achieved only using carrier suppression. This comparison is shown in Fig. 4(a). Clearly, carrier suppression with gain compensation show significant improvement as the carrier suppression level increases.

### 3.2. Noise performance enhancement

We further analyze the filter gain (G) enhancement and noise figure (NF) reduction of the filter using optical carrier suppression technique. The expression of noise figure (NF) can be described as

\[
NF = 174 - G + \left( N_{th} + \left( N_{RIN} + \frac{N_{sh}}{4} \right) \right)
\]  

(6)

where \( N_{th} = kT \), \( N_{RIN} = 10^{\frac{RIN}{10}}I_{dc}^2BR_L \), and \( N_{sh} = 2qI_{dc}BR_L \) are the noise power spectral density of thermal noise, relative intensity noise, and shot noise respectively with \( I_{dc} \) is the total DC photocurrent. Here, \( k \) is Boltzmann’s constant, \( q \) is electron charge, \( T \) is room temperature, \( B \) is
the noise bandwidth, and $R_L$ is the load resistance. The factor of $1/4$ in Eq. (6) occurs due to the use of impedance matching at the photodetector [17]. We measured the noise power spectral density in our filter using RF spectrum analyzer (RFSA). We ensure that the measured noise was dominated by the optical link noise instead of the displayed analyzer noise level (DANL) of the RFSA. From the measured values of RF link gain and noise power, we calculated the RF noise figure. The results are shown in Fig. 4(b), together with the calculated NF with RIN of -155 dB/Hz. In the same figure, we plot the calculated NF with EDFA compensation, showing NF degradation as expected. The best measured performance of our filter was -10 dB for filter’s gain and 27 dB for noise figure.

3.3. Comparison with conventional low biased MZM link

We further analyze the noise performance improvement technique because of the limitation that we encounter using optical ring resonator. Here, we build two microwave photonic link setups with intensity modulator (IM, Avanex FA20, 20 GHz). The first setup is set for the experiment of noise performance improvement technique using a Mach-Zehnder modulator with ring resonator (MZM + RR) and the second setup is set for the experiment with conventional low-biasing MZM (MZM + LB). The output optical field of intensity modulated signal, considering small signal modulation can be described as

$$E_{\text{in}}(t) = \frac{1}{2} \sqrt{P_i} e^{i\varphi_B} (1 + e^{i\varphi_B}) \sum_{n=-\infty}^{\infty} J_n(m) e^{i\omega_{RF}t}$$

(7)

Here, $\varphi_B = \pi V_{\text{DC}}/V_{\text{p,DC}}$ is the DC bias point, $V_{\text{DC}}$ is the input DC voltage and $V_{\text{p,DC}}$ is the DC half-wave voltage of the IM. Using the same approach for Eq. (4), the beating product of the photocurrent for setup with optical carrier suppression using optical ring resonator ($I_{\text{RR}}(t)$) and low-biased MZM ($I_{\text{LB}}(t)$) with gain compensation from EDFA can be described respectively as

$$I_{\text{RR}}(t) = \frac{1}{2} R_P P_i G_{\text{EDFA}} (1 + \cos \varphi_B) \begin{bmatrix} (\alpha^2 J_0^2(m) + 2J_1^2(m)) \\ +2\alpha J_0(m)J_1(m)\cos(\omega_{RF}t + \theta_a) \\ +2\alpha J_0(m)J_1(m)\cos(\omega_{RF}t - \theta_a) \end{bmatrix}$$

(8)

$$I_{\text{LB}}(t) = \frac{1}{2} R_P P_i G_{\text{EDFA}} (1 + \cos \varphi_B) \begin{bmatrix} (J_0^2(m) + 2J_1^2(m)) \\ +4J_0(m)J_1(m)\cos(\omega_{RF}t) \end{bmatrix}$$

(9)
We send a laser with output power 18 dBm to intensity modulator and set a constant detected optical power in photodetector at 5 dBm. The modulator bias point is set at quadrature ($\varphi_B = \pi/2$) for ring-based carrier suppression technique and variety of bias point ($\varphi_B = \pi/2 - \text{null}$) for low-biasing technique.

In Fig. 6(a) we plot the simulated and measured RF filter’s gain enhancement for both setups shown in Fig. 5. Here, the gain enhancement is defined as the ratio of gain at various carrier suppression and the gain at no carrier suppression. As expected, gain enhancement in the case of MZM + RR increase linearly with carrier suppression. In the case of low-biasing MZM, the rate of gain enhancement around quadrature is higher, but at higher suppression the rate is linear. When compared, low-biasing MZM leads to higher gain enhancement than MZM + RR. Similar behavior is observed in the NF reduction plotted in Fig. 6(b). From these results, low-biasing MZM is more beneficial than carrier suppression using ring resonator.

4. Discussion

As shown in Fig. 4, the optical ring resonator can only have limited suppression of around 6 dB. This is fundamentally limited by the mechanism of carrier suppression. To analyze the limitation of carrier suppression mechanism, we need to look at the power resonance in the cavity of optical ring resonator with multiple suppression. Here, the power enhancement ratio of optical ring
resonator can be described as [18]

\[ P_{\text{res}}/P_i = \left( \frac{2}{\pi} \right) \eta Q (\text{FSR}/\nu) \]  

(10)

where \( P_{\text{res}} \), \( \eta \), \( Q \), \( \lambda_{\text{res}} \), and \( \nu \) are power resonance in the cavity, the coupling efficiency, Q-factor, resonance wavelength and the frequency of the light in optical ring resonator respectively. In an optical ring resonator with 6 dB suppression, a high optical power in the optical carrier is being coupled to a low loss optical ring resonator with Q-factor of around \( 1.52 \times 10^6 \). It means that there is an optical power enhancement factor of 31.7 in the ring, and this will lead to resonance shift, leads to the reduction of optical carrier suppression, and compromise the stability of the system.

Therefore, a new architecture is required to mitigate this problem. An alternative for on-chip optical carrier suppression that can be considered include loss resonance of stimulated Brillouin scattering (SBS) waveguide [19] or a carrier re-insertion network commonly used in coherent detection architecture [20].

5. Conclusion

We have demonstrated on-chip programmable MWP filter with an integrated optical carrier suppression. The bandwidth of the bandpass filter can be tuned, and the noise performance can be enhanced with optical carrier suppression. Experimental results show that a filter gain of -10 dB, a tunable bandwidth of 6 GHz, a suppression up to 6 dB, and a minimum noise figure of 27 dB can be achieved using OC and UC optical ring resonators all integrated on-chip. The advantages of this technique are having more advanced functionality, flexibility, DC bias drift free, and able to enhance the noise performance of the filter, without adding complexity of optical components and massive reduction of PIC’s footprint.

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References

1. D. Marpaung, J. Yao, and J. Capmany, “Integrated microwave photonics,” Nat. Photonics 13(2), 80–90 (2019).
2. Y. Liu, J. Hotten, A. Choudary, B. J. Eggleton, and D. Marpaung, “All-optimized integrated RF photonic notch filter,” Opt. Lett. 42(22), 4631–4634 (2017).
3. L. Zhuang, C. Taddei, M. Hoekman, A. Leinse, R. Heideman, P. van Dijk, and C. Roeloffzen, “Ring resonator-based on-chip modulation transformer for high-performance phase-modulated microwave photonic links,” Opt. Express 21(22), 25999–26013 (2013).
4. N. Ehteshami, W. Zhang, and J. Yao, “Optically Tunable Single Passband Microwave Photonic Filter Based on Phase-Modulation to Intensity-Modulation Conversion in a Silicon-on-Insulator Microring Resonator,” Proc. Int. Top. Meet. IEEE Microw. Photon. (2015).
5. A. Choudary, I. Aryanfar, S. Shahnia, B. Morrison, K. Vu, S. Madden, B. Luther-Davies, D. Marpaung, and B. J. Eggleton, “Tailoring of the Brillouin gain for on-chip widely tunable and reconfigurable broadband microwave photonic filters,” Opt. Lett. 41(3), 436–439 (2016).
6. W. Wei, L. Yi, Y. Jaouen, and W. Hu, “Bandwidth-tunable narrowband rectangular optical filter based on stimulated Brillouin scattering in optical fiber,” Opt. Express 22(19), 23249–23260 (2014).
7. D. Zhang, X. Feng, and Y. Huang, “Tunable and Reconfigurable bandpass microwave photonic filters utilizing integrated optical processor on silicon-on-insulator substrate,” IEEE Photonics Technol. Lett. 24(17), 1502–1505 (2012).
8. Z. Zhang, B. Huang, Z. Zhang, C. Cheng, and H. Chen, “Microwave photonic filter with reconfigurable and tunable bandpass response using integrated optical signal processor based on microring resonator,” Opt. Eng. 52(12), 127102 (2013).
9. J. P. Salvestrini, L. Guilbert, M. Fontana, M. Abarkan, and S. Gille, “Analysis and control of the DC drift in LiNbO3-based Mach-Zehnder Modulators,” J. Lightwave Technol. 29(10), 1522–1534 (2011).
10. M. J. LaGasse, W. Charezenko, M. C. Hamilton, and S. Thaniyavarn, “Optical carrier filtering for high dynamic range fibre optic links,” Electron. Lett. 30(25), 2157–2158 (1994).
11. M. J. LaGasse and S. Thaniyavarn, “Bias-Free High-Dynamic-Range Phase-Modulated Fiber-Optic Link,” IEEE Photonics Technol. Lett. 9(5), 681–683 (1997).
12. Z. Zhu, Y. Liu, M. Merklein, O. Daulay, D. Marpaung, and B. J. Eggleton, “Positive link gain microwave photonic bandpass filter using Si3N4-ring-enabled sideband filtering and carrier suppression,” Opt. Express 27(22), 31727–31740 (2019).
13. H. Jiang, L. Yan, and D. Marpaung, “Chip-based arbitrary radio-frequency photonic filter with algorithm-driven reconfigurable resolution,” Opt. Lett. 43(3), 415–418 (2018).
14. L. Zhuang, C. Roeloffszen, M. Hoekman, K.-J. Boller, and A. J. Lowery, “Programmable photonic signal processor chip for radiofrequency applications,” Optica 2(10), 854–859 (2015).
15. W. Bogaerts, P. De Heyn, T. Van Vaerenbergh, K. De Vos, S. Kumar Selvaraj, T. Claes, P. Dumon, P. Bienstman, D. Van Thourhout, and R. Baets, “Silicon microring resonator,” Laser Photonics Rev. 6(1), 47–73 (2012).
16. C. G. H. Roeloffszen, M. Hoekman, E. J. Klein, L. S. Wevers, R. B. Timens, D. Marchenko, D. Geskus, R. Dekker, A. Alippi, R. Grootjans, A. van Rees, R. M. Oldenbeuving, J. P. Epping, R. G. Heideman, K. Worhoff, A. Leinse, D. Geuzbroek, E. Schreider, P. W. L. van Dijk, J. Visscher, C. Taddei, Y. Fan, C. Taballione, Y. Liu, D. Marpaung, L. Zhuang, M. Benelajla, and K. J. Boller, “Low-loss Si3N4 TriPleX optical waveguides: Technology and applications overview,” IEEE J. Sel. Top. Quantum Electron. 24(4), 1–21 (2018).
17. D. A. I. Marpaung, “High Dynamic Range Analog Photonic Links: Design and Implementation,” Ph.D. dissertation, Univ. of Twente, Enschede, The Netherlands, 2009.
18. C. K. Madsen and J. H. Zhao, “Optical Filter Design and Analysis,” Optical Filter Design and Analysis. 1999.
19. S. Tonda-Goldstein, D. Dolfi, J.-P. Huignard, G. Charlet, and J. Chazelas, “Stimulated Brillouin Scattering for microwave signal modulation depth increase in optical links,” Electron. Lett. 36(11), 944–946 (2000).
20. A. Meijerink, C. G. H. Roeloffszen, R. Meijerink, L. Zhuang, D. Marpaung, M. J. Bentum, M. Burla, J. Verpoorte, P. Joorna, A. Hulzinga, and W. van Etten, “Novel Ring Resonator-Based Integrated Photonic Beamformer for Broadband Phased Array Receive Antennas – Part I: Design and Performance Analysis,” J. Lightwave Technol. 28(1), 3–18 (2010).