

Integrated Tunable Phase Shifter Based on Energy-Conserved Phase Amplification and Its Application for RF-OAM Generation

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Integrated Tunable Phase Shifter Based on Energy-Conserved Phase Amplification and Its Application for RF-OAM Generation

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Abstract—Photonics-assisted microwave phase shifter is one of the essential components in communications. Phase amplification is a promising technology which efficiently enables compact photonics-assisted microwave phase shifter. Based on vector sum, the phase shift can be translated from amplitude attenuation to phase amplification. This issues an additional optical energy consumption and even more the highly dependent signal to noise ratio of phase-shifted microwave signal. In this paper, we propose an energy-conserved phase amplification concept to address this issue. Furthermore, based on this concept, we demonstrate a microwave photonic phase shift system with an integrated chip incorporating an arrayed waveguide gratings (AWG) structure. A multichannel continuous 360° phase shift over a frequency range of 12 GHz–20 GHz can be achieved by changing the optical carrier wavelength. Taking advantages of phase modulator and AWG structure, a reliable and efficient phase shifter for beam steering and orbital angular momentum (OAM) generation system can be realized without any other active device. The simulation results of OAM purity test show that better OAM beams can be obtained with the proposed phase shifter. This integration method has great potential in RF OAM generation and multiplexing system to improve the signal quality and reduce the system complexity.

Index Terms—Integrated microwave photonics, optical signal processing, phase amplification, phase shifters, RF-OAM.

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I. INTRODUCTION

BASED on the intensive study of microwave photonics, it is concluded that more and more researchers pay attention to the photonic integration to boost the optoelectronic system performance [1], [2]. A key optoelectronic technique, the radio frequency (RF) photonic phase shifter, is widely used in phased-array antennas communications [3], analog signal processing [4], and even the RF orbital angular momentum (OAM) generation system [5], [6]. Because of the advantages of wide bandwidth, large tunable range, and immunity to electromagnetic interference (EMI). The utilization of photonic integration in a phase shifting system becomes an efficient solution to fulfill the requirements, such as an ultrashort response time and fine-tuning resolution in a miniaturized system.

Various methods to realize photonics-assisted RF phase shifters have been proposed and reported, such as stimulating Brillouin scattering [7], [8], basing on optical-vector-sum technique [9], [10], using a fibre Bragg grating with a different phase response [11], [12], and taking advantages of polarization relations in signal modulations [13], [14]. With the support of diverse microwave photonics techniques [15], the independent phase shift in multichannel can be achieved in one system [16]. However, the above systems without integration technique always suffer from large power variation with phase shifting, high sensitivity to direct current (dc) drift of the Mach–Zehnder modulator (MZM), or high system complexity in the resender methods. In addition, with temperature variation and working time increase, the stability of the phase shifter is weakened. It is also difficult to achieve either very accurate phase control or system reconfiguration in practical applications.

Especially in the application of RF OAM generation, these additional effects will seriously affect the purity of the OAM beam. The OAM beam has a helical phase front comprising a spatial azimuthal phase term $\exp(il\varphi)$ (where l is the topological charge of OAM state, and φ is the transverse azimuthal angle) [17]. The RF OAM beam is very sensitive to the signal phase distribution. In another word, a stable phase shift without drifting is the basis of generating RF OAM without leaky states. Though the optical true time delay (OTTD) technique can eliminate the beam squinting, the phase difference, causing by the same time delay in one wideband signal, will distort the purity of the OAM states, owing to the phase term $\exp(il\varphi)$.

Unlike traditional beamforming systems, it is more appropriate to apply the phase shift technique in OAM generation, as a special beamforming, rather than applying the OTTD technique. However, the mainstream of RF OAM systems applies the spiral phase plate (SPP) [5] or intensity interferometer plate [18] to form the helical phase front until now, which in essence is the utilization of OTTD principle. With the OTTD technique, the disadvantages of bandwidth limitation will become apparent in OAM multiplexing communications. Owing to the complexity of these existing RF OAM generation systems, the realization of a beamforming system using a highly integrated RF photonic phase shift technique is imperative.

We propose a multichannel integrated photonic phase shifting system with a principle of phase amplification [19]. This allows a continuous phase shift ranging from -180° to 180° over a frequency range of 12 GHz–20 GHz. The RF phase can be tuned by changing the wavelength of a laser without any other active device. Because of the characteristics of the passive system, the additional effects in other methods such as phase drift will be avoided effectively. The way of wavelength control in the laser guarantees the stability of the whole system. The phase amplification is based on vector sum, which translates a phase shift to amplitude attenuation. A specially designed integrated looped-back arrayed waveguide gratings (AWG) which has demonstrated in previous work is used to realize the phase shift [20]. In this way, the utilization rate of signal energy can reach its maximum without additional loss. The whole system inherits the advantages of the wideband operation in the phase amplification and low insertion loss in the AWG. The low energy conversion rate in phase amplification can be avoided in the combination method. Besides, the AWG also provide new feature of continuous phase shift instead of only providing time delays in this scheme.

Actually, the AWG can be considered as optical time delay lines (OTDLs), which provides a 4-channel time delay in a period. Based on this feature, combining with the wavelength division multiplex (WDM) technique, the RF OAM beam can be easily generated in the proposed system. The integration method achieves the perfect fusion of OTTD and phase shift in a miniaturized system for RF-OAM communications and beamforming. Moreover, the combination of the beam steering and the generation of RF OAM is firstly verified in an optical control system with twice ingenious phase shifts [21]. In our proposal, the control of time delay and phase shift, a two-dimensional independent control, can be achieved in only one AWG structure at the same time, which has the potential to simplify the future communications system with steering RF OAM beams.

II. OPERATION PRINCIPLE OF ENERGY-CONSERVED PHASE AMPLIFICATION

A. Phase Amplification

The principle of the proposed phase shifter is phase amplification [19] based on a vector-sum operation, as shown in Fig. 1(a). A double sideband phase-modulated signal is applied in our system. The vectors in black $A_1 \cos(\omega t + \varphi_1)$ and blue $A_2 \cos(\omega t + \varphi_2 + \pi)$ represent the RF signals, where ω is the

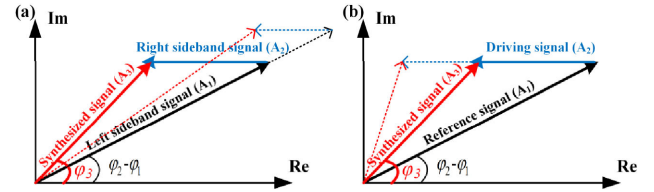


Fig. 1. (a) Principle of the proposed phase shifter. (b) Principle of general phase amplification technique.

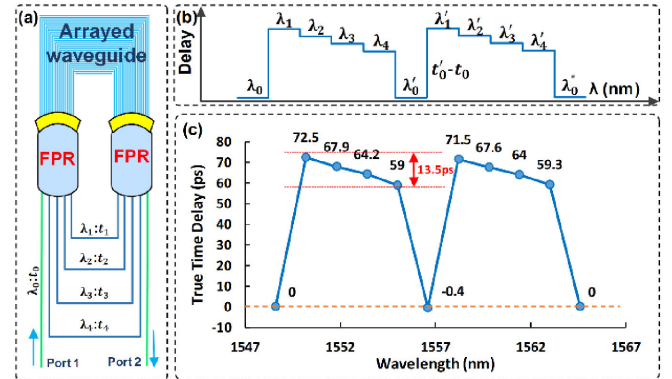


Fig. 2. (a) The looped-back AWG, (b) the spectral transmission of the looped-back AWG, and (c) the measured normalized true time delay in two periods. FPR: free propagation region.

signal frequency, coming from the upper and lower sidebands, respectively, with a phase difference of $\pi + \varphi_2 - \varphi_1$. The phase difference $\varphi_2 - \varphi_1$ contains two parts. One is an initial phase shift resulting from the dispersion characteristics of two sidebands in an actual transmission system. The other one is the phase difference introduced by an extra control method. A final RF signal depicted by a vector in red $A_3 \cos(\omega t + \varphi_3)$ can be obtained by synthesizing the sideband signals. It can be seen that the final signal phase φ_3 can be controlled by varying the amplitudes A_1 and A_2 as well as the phases φ_1 and φ_2 of the sideband signals. Therefore, the phase shift will be achieved by processing the optical modulated signals. It is worth noting that the energy of the driving signal is sacrificed to obtain the phase shifts with a constant reference signal in the general phase amplification scheme in Fig. 1(b) [19]. However, in our proposal, the two sideband signals are processed simultaneously to realize the energy conservation.

B. Passive Energy-Conserved Phase Amplification Based on Arrayed Waveguide Grating

The key device in the proposed system is the arrayed waveguide grating (AWG) feedback loop. This device is a stepwise OTTD [22] and it is used here as the optical signal processing method for shifting the phase. Fig. 2(a) is the topology of the looped-back AWG with four feedback paths, where the AWG acts as a 4-channel-wavelength multiplexer. In other words, the AWG loop involuntarily creates the conditions to process signals at different frequencies simultaneously, which perfectly matches the control principle of a phase shift as mentioned before. The

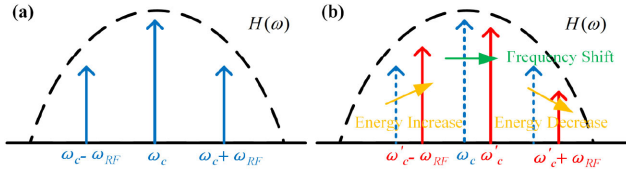


Fig. 3. The schematic diagram of the phase modulated signal intensity response in one channel. The optical signal frequency is changed from the blue arrows in (a) to the red arrows in (b).

delay in each channel can be expressed as $t_n(\lambda_n)$ ($n = 0, 1 \dots 4$) in one period. It is noticeable that $t_0(\lambda_0)$ is the baseline channel (1547.8 nm–1549.4 nm) of the AWG structure, in which the optical signal will go through without passing the feedback loop. Therefore, the signal intensity in channel ‘0’ is slightly stronger. The time delay t_0 in channel ‘0’ is normalized to 0 ps to act as a reference. Fig. 2(b) depicts the delay response of the looped-back AWG OTDL with a cyclic characteristic. The free spectral range (FSR) of the AWG in one period is 8 nm (1000 GHz) with 1.6 nm (200 GHz) channel spacing. As shown in Fig. 2(c), the measurement delays of five channels over a period ranging from 1547.8 nm to 1555.8 nm (λ_0 to λ_4), are 0 ps, 72.5 ps, 67.9 ps, 64.2 ps, 59 ps. Owing to the separated channels for different wavelengths in AWG structure, different phase shifts can be achieved simultaneously with multi-wavelength carriers independently. Therefore, different phase and intensity responses, causing different delays, can be obtained in different feedback loops for each wavelength.

C. Criteria of a Flat Phase Response

The phase control is described with an example of a combination of phase amplification and AWG. To analyze the signal more clearly, the initial phases of carrier and sidebands signals are set as 0° . When an optical carrier with frequency ω_c is modulated by an RF signal with frequency ω_{RF} , the electric field of the output signal after the phase modulator is given by:

$$E_{out}(t) = A_l \exp[j(\omega_c - \omega_{RF})t + j\varphi_1] + A_c \exp(j\omega_c t) + A_r \exp[j(\omega_c + \omega_{RF})t + j(\varphi_2 + \pi)], \quad (1)$$

where A_c , A_l and A_r are the amplitudes of the optical carrier, the left sideband, and the right sideband, respectively. As shown in Fig. 3(a), the phase modulated optical signal is filtered twice by the AWG link. Owing to the AWG link characters, optical signals will go through and be fed back to AWG structure again with a total intensity response of $H(\omega)$. Then two final independent RF signals resulted from beating frequencies between two sideband signals and carrier can be expressed as $A_1 \exp(j\omega t + j\varphi_1)$ and $A_2 \exp(j\omega t + j\varphi_2 + j\pi)$, where A_1 and A_2 are the corresponding amplitudes. The final output signal $\{A_1 + A_2 \exp[j(\pi + \varphi_2 - \varphi_1)]\} \exp[j(\omega t + \varphi_1)]$ can be expressed in a complex form $a + jb$, which a is the real part and b is the imaginary part of the signal. The phase of the final RF signal φ_3 can be expressed with the following equation:

$$\cot \varphi_3 = \frac{a}{b} = \frac{A_1 + A_2 \cos(\pi + \varphi_2 - \varphi_1)}{A_2 \sin(\pi + \varphi_2 - \varphi_1)}. \quad (2)$$

In addition, another RF signal of φ'_3 is obtained by changing the optical carrier frequency to ω'_c . To achieve the phase shift, the phase difference $\varphi_3 - \varphi'_3$ between any two synthesized signals should be constant but not equal to 0. Obviously, the value of $\cot \varphi_3 - \cot \varphi'_3$ also should be a constant. A'_1 and A'_2 are the corresponding amplitudes of the RF signal with the carrier frequency ω'_c . The expression of $\cot \varphi_3 - \cot \varphi'_3$ can be written as

$$\cot \varphi_3 - \cot \varphi'_3 = \left(\frac{A_1}{A_2} - \frac{A'_1}{A'_2} \right) / \sin(\pi + \varphi_2 - \varphi_1). \quad (3)$$

Because of the frequency shift, the intensities of the sidebands and carrier are changed as illustrated in Fig. 3(b). Owing to the relations of $A_1 \propto \sqrt{H(\omega_c)H(\omega_c - \omega_{RF})}$ and $A_2 \propto \sqrt{H(\omega_c)H(\omega_c + \omega_{RF})}$, the function of $\cot \varphi_3 - \cot \varphi'_3$ for a given RF signal depends only on ω_c and ω'_c . If the intensity response $H(\omega)$ of the two-round AWG link obeys a Gaussian distribution, (3) can be simplified as:

$$\cot \varphi_3 - \cot \varphi'_3 = K \left(\sqrt{\frac{H(\omega_c - \omega_{RF})}{H(\omega_c + \omega_{RF})}} - \sqrt{\frac{H(\omega'_c - \omega_{RF})}{H(\omega'_c + \omega_{RF})}} \right) = C, \quad (4)$$

where $K = 1/\sin(\pi + \varphi_2 - \varphi_1)$ and C is a non-zero constant for a given frequency ω'_c . Moreover, C can be calculated with the Gaussian characteristic parameter of the AWG structure. Based on the characteristics of the Gaussian shape, the total output power will not change much when the carrier is moving around the center frequency in the flat area of one channel. According to the above derivations and analysis, the parameters of the AWG structure can be designed and modified.

When the frequency of the carrier is moving in one channel, the intensities of the sideband signals will vary with the Gaussian shape filter of the AWG structure. It is equivalent that two intensity-tunable single sideband signals transmit in one optical path with a fixed time delay, which is related to the selection of the channels. With different amplitudes (A_1 and A_2) and an initial phase difference $\varphi_2 - \varphi_1$ induced from an optical resonance of the whole link, a continuous 360° phase shift can be realized in an AWG structure. In addition, the modulated optical signal passes through only one AWG channel, so the signal power can be totally retained to get a stable signal to noise ratio. Unlike the traditional vector sum technique [10], the energy increase in one sideband signal will cause the energy decrease of the other one naturally in Fig. 3(b). Therefore, the combination of AWG and phase amplification ensures the energy conservation. In general, the phase of the synthesized RF signal can be controlled by tuning the wavelength of the optical carrier without any other active device.

III. EXPERIMENTS SETUP AND RESULTS

To further prove the theory in applications, the measurement setup of the proposed microwave photonic phase shift system using an AWG structure is illustrated in Fig. 4. The setup consists

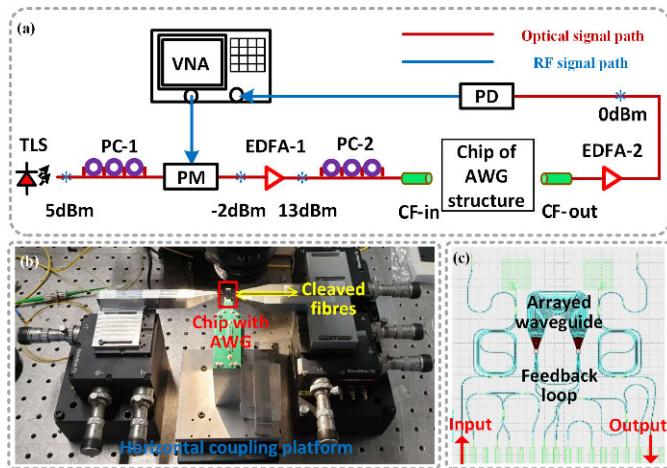


Fig. 4 (a) Schematic diagram of the proposed microwave photonic phase shifter; (b) The photo of chip test platform; (c) The chip design of AWG structure. TLS: tunable laser source; PM: phase modulator; PC: polarization controller; EDFA: Erbium-doped fibre amplifier; CF-in: cleaved input single-mode fibre; AWG: arrayed waveguide gratings; CF-out: cleaved output single-mode fibre; PD: photodiode; VNA: vector network analyzer.

of a tunable laser source, a phase modulator (PM), two Erbium-doped fibre amplifiers (EDFA), a chip incorporating an AWG structure, two polarization controllers (PC), a photodiode (PD) and a vector network analyzer (VNA). A tunable optical carrier with an output power of 5.00 dBm is generated by a tunable laser and fed into a PM (EOSPACE PM-5K5-20-PFA-PFA-UV) through a PC-1. A radio frequency signal ranging from 12 GHz to 20 GHz generated by a VNA is modulated on the PM. After the modulation, an EDFA is used to boost the power of a modulated signal from -3 dBm to 13 dBm. With the help of the characteristics of the AWG structure, a PC-2 is employed to align optical polarization to the pure TE polarization. Two cleaved single-mode fibres (CF) are employed to couple the light into and out of the waveguides on the AWG structure, aiming to optimize the coupling and reduce the insertion loss. The total insertion loss of the AWG structure is ranging from 17.5 dB to 21.5 dB in different channels. Therefore, EDFA-2 is applied before receiving to amplify the optical power to 0 dBm to keep the PD (XPDV2120RA) working in the linear range. Finally, the modulated optical signal is detected by a PD and fed back to the VNA. The optical power of each key position has been marked in Fig. 4. When the wavelength of the optical carrier is changed, only the signal phase will be affected on account of the AWG responses. Hence, based on phase amplification, a continuous wide-band RF independent 360° phase shift can be obtained by controlling the laser wavelength to match different areas of the channel in the AWG structure.

Figure 5 shows the phase responses of the proposed phase shifter. A nearly flat phase within a frequency range between 12 GHz to 20 GHz in a tunable laser wavelength ranging from 1549.9 nm to 1550.5 nm is obtained. The 0° phase line is normalized at 1550.2 nm, which is the center of one channel. Because of the introduction of fibre coupling and EDFA-2, there are some variations on the phase lines, which can be eliminated

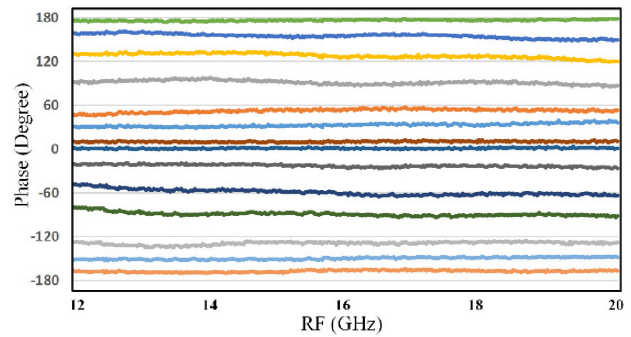


Fig. 5. Experimentally generated phase shift over a frequency range of 12 GHz to 20 GHz.

after packaging and using program control. In addition, based on the trend of these curves in figure 5, the whole system has the potential for a phase shift over 20 GHz, which is not measured here. A VNA with higher bandwidth will be helpful for the result. Actually, according to the principle of the proposed phase shifter, the phase shift is always satisfied in one channel with enough bandwidth, keeping the two sideband signals in both sides of the channel. If one of the sideband signal crosses the center of the channel, the phase amplification will be invalid without a monotone variation of the signal intensity. The phase shift over 20 GHz can be obtained with proper channel space in a new design, and measured with a high bandwidth VNA. By adjusting the laser wavelength to select the signal spectrum position in the channels of the AWG to obtain different responses of the sideband signals, the phase of the RF signal is tuned from -180° to 180° . The bandwidth and the precision of the phase shift can be increased by changing the FSR and the delays of different channels. Even the tolerance of errors during the progress of adjustment can be improved. The chip in the present system has an FSR of 1000 GHz and the delays between channels are about 4 ps, which can be changed easily during the chip design process. Based on these two methods to modify the AWG structure, the sensitivity of the signal phase to optical wavelength can be reduced effectively by a wider FSR and a smaller delay.

IV. ANALYSIS

To verify the feasibility of this phase shift structure in RF-OAM communication system, some simulations have been done. The results of the transmission experiments of the RF-OAM beam with the proposed chip design will be explained in detail in future work with the help of a complete signal transmission system. An ideal OAM beam of 20 GHz with the state of $l = 1$ is simulated in Matlab, the phase distribution at the receiving plane is shown in Fig. 6(a). Due to the orthogonality of the OAM states, the purity of OAM state can be detected by comparing the products of the phase information at one receiving plane with different ideal OAM beams [23]. The phase term $\exp(il\varphi)$ can be eliminated by the opposite OAM state of $-l$. The product of two opposite states should be a constant. Otherwise, the product should be equal to zero. If the target OAM mode converts to the nearby modes, the value of the product will grow up. Based on

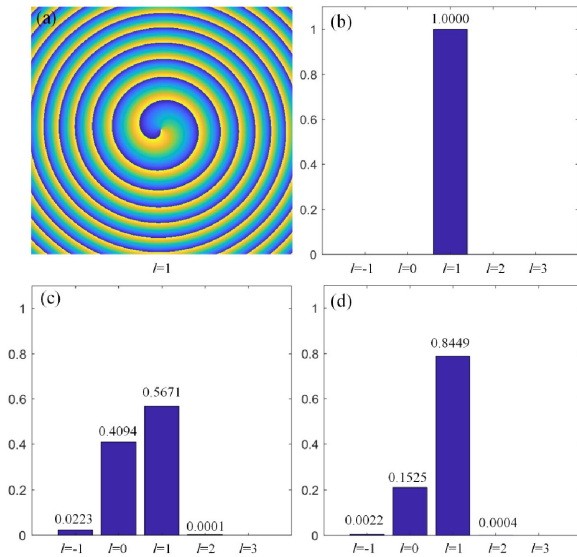


Fig. 6. The purity analysis of OAM beams with different generated sources. (a) Ideal OAM beam. (b) Purity with ideal phase shift signals. (c) Purity with time delay signals. (d) Purity with AWG phase shift signals.

the above orthogonality, the mode purities of OAM beams can be depicted with different generated sources in Fig. 6(b), 6(c), and 6(d). Another four nearby OAM states are normalized as the references in these figures. It is worth noting that all these RF-OAM beams are generated in a 4-antenna array mode in the simulation using the circular antenna array (CAA) with a radius of 1.5 cm (the wavelength of the 20 GHz signal) [6]. To simply the model, spherical waves are used as the beam sources for the OAM beam generation. The propagation distance is set to 45 cm (30 times the wavelength) to ensure the OAM far-field pattern. In addition, the ideal OAM beam for detection at the receiving plane is generated by a 16-antenna array to obtain credible results for actual applications.

To realize the applications in broadband communication, the purity is checked at 19 GHz with 1 GHz offset from the center frequency. In Fig. 6(b), four ideal phase shift signals are employed, and the purity result shows that there is no crosstalk from other OAM states. In Fig. 6(c), with the true time delay (TTD) technique, 4-path 2 GHz bandwidth signals with a time delay space of 12.5 ps is generated at 20 GHz. In this way, a phase drift of 4.5° at 19 GHz is introduced. As shown in Fig. 6(c), this drift decreases the state purity of the OAM, which indicates that time delay can only be applied in a narrow bandwidth case for an OAM system. In Fig. 6(d), the phase shift results from the AWG structure, we proposed, is applied. The phase information of 0° , 90° , 180° , and -90° from the previous experiment using a different carrier are chosen as the driving sources of the OAM beam. The leaky states are caused by the slight phase deviation in our phase shift proposal. Obviously, the mode purity performs better in our integrated phase shift method with a wideband signal. Similar conclusions can be obtained with different CAA in some other applications [24].

It is worth noting that the wavelengths of the carriers are set to 1534.2 nm, 1542.2 nm, 1550.2 nm, and 1558.2 nm

originally to confirm the channels in the OAM generation with the state of $l = 1$. Then four paths tunable phase shifts can be realized independently by adjusting the wavelength finely in the corresponding channels with the same time delay. If other wavelengths are picked, different time delays can be obtained which will lead also to an OAM beam steering [21]. In this way, the complex RF-OAM generation combined with a control system can be designed on a single chip. Additionally, other OAM states can be realized for multiplexing in the same way within different channels at the same time. For example, the wavelengths of the carriers can be set at 1538.2 nm, 1546.2 nm, 1554.2 nm, and 1562.2 nm for another OAM beam with the state of $l = -1$. In this case, the phase information of 0° , -90° , -180° , and 90° are applied in the 4 picked channels. Because of the different operation channels, different OAM states can be multiplexed directly by using wavelength-division multiplexing. More channels and different phase shifts can be used for higher OAM states in the same way for multiplexing. Therefore, this chip, incorporating AWG and the integrated multichannel phase shift method, is appropriate for RF-OAM communication system.

V. CONCLUSION

In general, a multichannel integrated photonic phase shifting system with a continuous phase shift ranging from -180° to 180° over a frequency range of 12 GHz to 20 GHz can be achieved designed on a single chip incorporating an AWG structure. Based on the principle of phase amplification, the RF phase can be tuned by changing the wavelength of the laser without any active device. This integration method has great potential in RF-OAM multiplexing communications system to improve the signal quality and reduce the system complexity. Another set of chips will be redesigned to modify the intensity and the time delay for applications in our future work.

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