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Ultra-wide bandwidth photonic microwave phase shifter with amplitude control function

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Abstract: This paper presents a new technique for realizing continuous 0°-360° RF signal phase shift over a very wide bandwidth. It is based on using single-sideband modulation together with optical filtering to largely suppress one of the RF modulation sidebands over a wide input RF frequency range, and controlling the phase of the optical carrier to shift an RF signal phase. The technique does not require expensive electrical or optical components to realize an RF signal phase shift over 2–40 GHz frequency range with a flat amplitude and phase response performance. This overcomes the current technology limitation in which no reported phase shifter structure has demonstrated the capability of operating in such a wide bandwidth. Experimental results demonstrate only ± 1 dB amplitude variation and ± 5° phase deviation from the desired RF signal phase shift over 2–40 GHz bandwidth and the RF signal amplitude control function. The phase shifter wavelength insensitive performance is also demonstrated experimentally.

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References and links


1. Introduction

Microwave photonic technologies have been employed in designing electronics warfare systems [1]. The main reason is microwave photonic devices have the potential of wide bandwidth. Other reasons include high resolution, wide tunability and immune to electromagnetic interference [2].

Shifting an RF signal phase, which can be accomplished by a phase/time shifter, is an important function in beamforming radar systems. Many microwave photonic techniques to realize an RF signal phase shift have been reported but very few of them have demonstrated broadband phase shifting operation [3–7]. Among these broadband phase shifters, none of them have the ability to realize flat amplitude and phase response over the 2–40 GHz frequency range, which is an operating frequency range for modern electronic warfare systems [8]. For example Pan et al. demonstrated a wide bandwidth phase shifter based on a polarization rotation technique [4]. However, the experimental results show large reduction in the output RF signal amplitude at the frequencies below 10 GHz. This is due to the technique relies on using an optical filter to remove one RF modulation sideband and a practice optical filter has a limited edge roll-off factor. Hence the unwanted RF modulation sideband at the frequencies close to the carrier frequency cannot be largely suppressed, which alters the output RF signal amplitude. An ultra-sharp edge roll-off optical filter, e.g. a 1500 dB/nm edge roll-off optical filter from Alnair Labs, can be used to extend the phase shifter lower operating frequency but it is expensive, and most importantly both the optical filter and the laser source wavelengths need to be critically controlled, otherwise a small change in either one of these wavelengths will result in change in the output RF signal amplitude.

The aim of this paper is to present a new photonic microwave phase shifter structure that has a 2–40 GHz bandwidth to fill in the current technology gap. The phase shifting operation is based on the beating of a single RF modulation sideband and an optical carrier with an adjustable optical phase. An interesting feature of this phase shifter is the suppression of the unwanted RF modulation sideband is realized by a hybrid technique of using single sideband (SSB) modulation at low RF signal frequencies and using a low-cost optical filter at high RF signal frequencies. The phase shifter is demonstrated experimentally with the results showing only ±1 dB amplitude variation and ±5° phase deviation for the full 0°–360° phase shift range over the phase shifter bandwidth of 2–40 GHz. Experimental results also demonstrate the phase shifter has a wavelength insensitive performance.

2. Topology and principle of operation

The structure of the new photonic microwave phase shifter is shown in Fig. 1. It consists of a commercial dual-polarization dual-parallel Mach Zehnder modulator (DPMZM) formed by two DPMZMs connected in parallel with a 90° polarization rotator at the output of one of the DPMZMs. The two orthogonally polarized optical signals are combined via a polarization beam combiner (PBC). The top DPMZM inside the dual-polarization DPMZM is driven by
two 90° phase difference RF signals from a 90° hybrid coupler, which is formed by two cross-over transmission lines [9]. When an RF signal is introduced at the hybrid coupler input port, half the power flows to the 0° port and the other half is coupled to the 90° port. The top DPMZM is biased in the way to generate a single-sideband suppressed carrier (SSB-SC) RF modulated optical signal [10]. The bottom DPMZM is biased to pass the optical carrier where the optical carrier phase can be controlled via the DC voltage \((V_{b3})\) into the optical phase shifter inside this DPMZM. The optical carrier at the output of the bottom DPMZM passes through a 90° polarization rotator, which rotates the polarization state of the optical carrier by 90°. A 90° polarization rotator can be implemented by a half wave plate that has an optical axis with an angle of 45° to the slow axis of the modulator or using a liquid crystal twisted nematic cell [11], which are commercially available. A 45° polarizer can be used to convert the carrier at the bottom DPMZM output and the sideband at the top DPMZM output to have the same polarization state. The carrier and the sideband beat at the photodiode generating an RF signal with the phase, which is the same as the optical phase difference between the carrier and the sideband.

![Diagram](image)

Fig. 1. (a) Topology of the new ultra-wide bandwidth photonic microwave phase shifter and (b) the carrier (red line) at the bottom DPMZM output, and the carrier and sideband (black line) at the top DPMZM output. The frequency response of the optical filter used in the phase shifter structure (dashed line).

Note that a 90° hybrid coupler is used in the phase shifter structure to split the input RF signal into two with 90° phase difference in order for the top DPMZM to generate one RF modulation sideband with the carrier being suppressed. The frequency response at the 0° and 90° output ports of a commercial 2–26.5 GHz bandwidth 90° hybrid coupler was measured and is shown in Fig. 2. This shows the two coupler outputs have small 2.2 dB amplitude difference and small ± 3.5° phase difference from 90° within the coupler bandwidth. The figure also shows outside the coupler bandwidth, the RF signal amplitude at the coupler 90° port
reduces, on the other hand the RF signal amplitude at the coupler 0° port increases by around 3 dB. Using this 90° hybrid coupler at the DPMZM input, SSB-SC modulation can be obtained within the coupler 2–26.5 GHz bandwidth. Outside this frequency range, the two 90° phase difference RF signals into the DPMZM have large amplitude difference and hence the modulator acts as a double sideband suppressed carrier (DSB-SC) modulator as can be seen in Fig. 1(b). Figure 1(b) shows the carrier at the frequency $f_c$ and the sidebands at the output of the top DPMZM when the modulator is driven by RF signals with frequencies above 2 GHz from a 2–26.5 GHz bandwidth 90° hybrid coupler. This shows the carrier and the unwanted left sideband within the coupler bandwidth are suppressed. An optical filter with a response as shown in dashed line in Fig. 1(b) can be used to suppress the unwanted left sideband at the frequencies of more than 26.5 GHz away from the carrier. Since the optical filter is only responsible for suppressing the unwanted sideband at the frequencies far away from the carrier, it does not require to have a sharp edge roll-off factor. An inexpensive optical filter with a moderate edge roll-off factor of $> 120$ dB/nm can suppress the unwanted sideband at the frequencies of more than 26.5 GHz away from the carrier by over 25 dB. This shows large suppression of the unwanted sideband over a very wide frequency range can be obtained by using the hybrid SSB modulation and optical filtering technique. The bandwidth of the phase shifter is only limited by the dual-polarization DPMZM bandwidth, not the electrical 90° hybrid coupler bandwidth. Since the dual-polarization DPMZM is implemented using the electro-optic technology and an electro-optic modulator with a bandwidth of 75 GHz has been demonstrated [12], the phase shifter can be designed to operate beyond the 2–40 GHz band into the V band (40–75 GHz).

In addition to the phase shifting operation, the structure shown in Fig. 1(a) is also capable to control the RF signal amplitude. This is simply done by controlling the bias voltage ($V_{b1}$ or $V_{b2}$) into one of the MZMs inside the bottom DPMZM to alter the optical carrier amplitude. The change in the carrier amplitude converts into an RF signal amplitude change after photodetection. This shows RF signal modulation, phase shifting operation and amplitude control function are performed in a single unit. Both the phase shifting operation and the amplitude control function can be realized by adjusting one DC bias voltage into the modulator. Bias controllers for dual-polarization DPMZMs are commercially available. Using a bias controller not only can avoid the bias drift problem in a dual-polarization DPMZM but can also control the output RF signal amplitude and phase. Note that a phase shifter based on a dual-polarization DPMZM has been reported [13] but it has a different operation principle. In [13], the phase shifting operation is realized by using a polarization dependent optical phase shifter connected after the dual-polarization DPMZM to introduce different optical phases to the orthogonally polarized sideband and carrier at the dual-polarization DPMZM output. A polar-
ization dependent optical phase shifter is not required in the proposed phase shifter presented in this paper, which simplifies the phase shifter structure. Shifting the RF signal phase is obtained by controlling a bias voltage into the dual-polarization DPMZM to tune the optical carrier phase. Another novelty of the proposed phase shifter is that it is capable to control the RF signal amplitude by adjusting a modulator bias voltage to alter the optical carrier amplitude. Most importantly, the novel hybrid SSB modulation and optical filtering technique presented in this paper enables the proposed phase shifter to be operated over a wide 2 to 40 GHz frequency range using a 90° hybrid coupler with only 2 to 26.5 GHz bandwidth. The phase shifter presented in [13] requires a 2 to 40 GHz bandwidth 90° hybrid coupler with small amplitude and phase imbalance to realize the 2 to 40 GHz phase shifting operation, however such coupler is not commercially available. It should be pointed out that a 4 to 40 GHz phase shifting operation has been demonstrated [14] using the phase shifter structure presented in [13] with a 4 to 40 GHz bandwidth 90° hybrid coupler to split the input RF signal into two with 90° phase difference. However, the experimental results show the phase shifter has large amplitude variation and phase deviation due to the large phase imbalance of the commercial 4 to 40 GHz bandwidth 90° hybrid coupler, which degrades the phase shifter performance. The proposed phase shifter not only can operate over a wider frequency range using a narrower bandwidth 90° hybrid coupler but also has a better amplitude variation and phase deviation performance than that presented in [14].

3. Analysis

Assuming the dual-polarization DPMZM is driven by a single frequency RF signal and the input RF signal is a small signal, the phase shifter output electric field into the photodiode is given by

$$E_{out}(t) = \frac{E_{in}}{2} \sqrt{1 - t_f^2 L_{Pol} L_{OF}} \left[ \cos \left( \frac{\pi V_{b2}}{V_z} \right) \cos \left( \omega t + \frac{\pi V_{b3}}{V_z} \right) + \beta_{RF} \sin \left( \omega t - \omega_{RF} \right) \right]$$

where $E_{in}$ is the electric field amplitude at the dual-polarization DPMZM input, $t_f$ is the insertion loss of each DPMZM inside the dual-polarization DPMZM where the 90° polarization rotator and the PBC inside the modulator are assumed to have a small negligible loss, $L_{Pol}$ is the polarizer insertion loss, $L_{OF}$ is the optical filter insertion loss, $V_z$ is the modulator switching voltage, $\beta_{RF} = \pi V_{RF}/V_m$, $V_{RF}$ is the input RF signal amplitude, $\omega_z$ is the optical carrier angular frequency and $\omega_{RF}$ is the input RF signal angular frequency. Since the unwanted RF modulation sideband can be largely suppressed by the hybrid SSB modulation and optical filtering technique, it was neglected in (1). Note that due to the amplitude and phase imbalance of the 90° hybrid coupler and the different transmittance in different path of the DPMZM, the optical carrier at the output of the top DPMZM cannot be fully suppressed. However, its amplitude is much smaller than that passes through the bottom DPMZM. Hence the residual carrier at the output of the top DPMZM was neglected in (1) to simplify the analysis. Since the optical power is the electric field square and the photocurrent is the product of the photodiode responsivity $R$ and the optical power, the photocurrent at the RF signal frequency is given by

$$I_{RF} = \frac{-\sqrt{P_{in} \beta_{RF} \cos \left( \frac{\pi V_{b2}}{V_z} \right) \sin \left( \omega_{RF} t + \frac{\pi V_{b3}}{V_z} \right)}}{4}$$

where $P_{in}$ is the optical power into the dual-polarization DPMZM. The output electrical RF signal power and phase can be obtained from (2) and are given by

$$P_{RF, out} = \frac{R^2}{32} \sqrt{P_{in} \beta_{RF}^2 L_{Pol}^2 L_{OF}^2} \cos \left( \frac{\pi V_{b2}}{V_z} \right)$$

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\[
\theta_{RF,\text{out}} = \frac{\pi V_{b3}}{V_\pi}
\]

where \( R_o \) is the photodiode load resistance. Equation (3) and (4) show the output RF signal amplitude and phase can be controlled by the DC bias voltage \( V_{b2} \) and \( V_{b3} \) into the bottom DPMZM of the dual-polarization DPMZM respectively. The linearity of the proposed photonic microwave phase shifter was investigated by comparing the phase shifter output harmonic components with that of a conventional fiber optic link formed by a laser source, a Mach Zehnder modulator and a photodetector using VPITransmission Maker photonic simulation software. The simulation results show both the proposed phase shifter and a quadrature-biased fiber optic link do not generate the second order harmonic component. The ratio of the third order harmonic component power to the output RF signal power of the proposed phase shifter has < 1 dB difference compared to that of a quadrature-biased fiber optic link when the two systems are operated under the same condition, i.e. the same input RF signal power and the same modulator switching voltage. This shows the proposed photonic microwave phase shifter and a conventional fiber optic link have a similar linearity performance.

The gain of the ultra-wide bandwidth photonic microwave phase shifter, which is defined as the ratio of the output electrical RF signal power to the input electrical RF signal power into the 90° hybrid coupler, can be obtained from (3) and is given by

\[
G = \frac{P_{RF,\text{out}}}{P_{RF,\text{in}}} = \frac{R^2 L_{Pol}^2 L_{OF}^2}{32} \left( \frac{\pi}{V_\pi} \right)^2 \cos^2 \left( \frac{\pi V_{b2}}{V_\pi} \right) L R_{in} R_o
\]

where \( L \) is the 90° hybrid coupler insertion loss and \( R_{in} \) is the modulator input resistance. Equation (5) shows the proposed phase shifter has a loss of \( L_{Pol}^2 L_{OF}^2 \) compared to the conventional DPMZM based phase shifter [15]. Since the insertion loss of a typical optical filter \( L_{OF} \) and polarizer \( L_{Pol} \) is < 1 dB, the proposed phase shifter gain is < 4 dB below the conventional DPMZM based phase shifter gain. The proposed phase shifter does not generate additional noise components other than the laser intensity noise, the shot noise and the thermal noise, which are the fundamental noise components in a fiber optic link. This is another advantage of the proposed photonic microwave phase shifter compared with previously reported phase shifters, which generate additional noise components. For example a phase shifter based on slow light in semiconductor optical amplifiers (SOAs) [3] has a high signal spontaneous beat noise since SOAs have a high noise figure. Compared to the phase shifter based on stimulated Brillouin scattering [16], which relies on a long fiber as a Brillouin medium and requires two separated modulators and a microwave signal generator to tune the RF signal phase, the proposed phase shifter has a compact structure. The dual polarization DPMZM based phase shifter involves only a single laser source and a single photodetector whereas previously reported phase shifters require two photodetectors for differential detection [17] or two lasers where one is used as an optical source and the other is used for tuning the RF signal phase [5]. The noise figure is defined as the ratio of the total phase shifter output noise power to the product of the input noise power and the phase shifter gain. Since the noise figure is inversely proportional to the link gain [18], using a high-power laser source and/or a dual-polarization DPMZM with low switching voltages can improve both the phase shifter gain and noise figure performance.
4. Experimental results

Experiments were set up as shown in Fig. 3 to verify the principle of the ultra-wide bandwidth photonic microwave phase shifter. The laser source (Keysight N7714A) had a 1550 nm wavelength and a polarization maintaining fiber supporting TE mode in slow axis. The output of the laser was connected to a dual-polarization DPMZM (Fujitsu FTM7977HQA), which also had a polarization maintaining fibre at both the input and output ports. This modulator was a Titanium indiffused Lithium Niobate (Ti:LiNbO₃) waveguide optical modulator. It was initially designed for 128 Gbps dual-polarization quadrature phase shift keying (QPSK) transmission. The 6 dB optical bandwidth of this modulator was around 45 GHz. A 2–26.5 GHz bandwidth 90° hybrid coupler, which had the frequency response as shown in Fig. 2, was connected to the upper DPMZM of the dual-polarization DPMZM. A compact modulator bias controller (PlugTech MBC-DPIQ-01) was used to provide the bias voltages to the modulator. The DC voltages generated by the bias controller were set to obtain a SSB-SC RF modulated optical signal at the output of the upper DPMZM. One of the MZMs in the lower DPMZM was biased at the minimum transmission point and the DC voltage ($V_{b2}$) into another MZM was used to adjust the optical carrier amplitude for the amplitude control function. The DC voltage ($V_{b3}$) into the optical phase shifter inside the lower DPMZM was used to control the optical carrier phase. It should be pointed out that the bias controller is not an essential component in the phase shifter structure but it can largely simplify the modulator bias voltage control and can ease the modulator bias drift problem. The polarization controller and the polarizer in the setup were functioned as a 45° polarizer to convert the orthogonally polarized carrier and sideband to have the same polarization state. An erbium-doped fiber amplifier (EDFA) was connected to the polarizer output to compensate for the system loss. A 1 nm bandwidth optical filter, which had a roll-off factor of around 280 dB/nm, was used to filter out one RF modulation sideband at high frequencies and to suppress the amplified spontaneous emission noise. The output optical signal was detected by a 50 GHz bandwidth photodiode (U2t XPDV2120R), which was connected to a 43.5 GHz bandwidth vector network analyzer (VNA) (Keysight N5224A) to display the phase shifter amplitude and phase response.
Firstly, the two MZMs of the lower DPMZM inside the dual-polarization DPMZM were biased at the maximum and minimum transmission point respectively. The optical spectrum before and after the optical filter were measured as shown in Fig. 4 when the modulator was driven by a 15 GHz and 30 GHz RF signal respectively. It can be seen from Fig. 4(a) that the dual-polarization DPMZM was operated as a SSB and double sideband modulator when the input RF signal frequency was inside and outside the 90° hybrid coupler bandwidth respectively as was discussed in Section 2. Note that there exists a residual sideband at 15 GHz away from the carrier even the frequency of the input RF signal was within the 90° hybrid coupler bandwidth as shown in Fig. 4(a). This residual sideband was caused by the small amplitude and phase imbalance at the two 90° hybrid coupler output ports. However, this residual sideband is more than 28 dB below the right sideband and hence it has a negligible effect to the phase shifter performance. Moreover, the residual sideband was located at the falling edge of the optical filter, which further suppressed the residual sideband as shown in Fig. 4(b). Figure 4(b) shows that, after the optical filter, the left sidebands at 15 and 30 GHz away from the carrier were completely filtered out so that SSB modulation was obtained even the frequency of the input RF signal was outside the 90° hybrid coupler bandwidth. It should be pointed out that the amplitude of the right sideband at 30 GHz was 5.2 dB lower than that at 15 GHz. This was caused by the loss of the system components, such as the RF cables, the 90° hybrid coupler and the modulator, increases as the RF signal frequency increases.
The amplitude and phase responses of the phase shifter when $V_{b3} = 0$ V were recorded as the calibrated responses using the VNA. They were used to remove the frequency-dependent characteristic of the modulator, the photodetector and the electrical cables used in the experiment [3,19]. The amplitude and phase responses of the phase shifter relative to the calibrated responses were measured over the 2–43.5 GHz frequency range for different phase shifts by altering the bias voltage ($V_{b3}$) into the bottom DPMZM using the modulator bias controller, and the results are shown in Fig. 5. Note that the y-axis in the amplitude response shown in Fig. 5(a) is the ratio of the RF signal amplitude coming out from Port 2 of the VNA to the RF signal amplitude entering Port 1 of the VNA after the calibration process. The same applies for the amplitude responses in the subsequent figures. The experimental result demonstrates a continuous $-180^\circ$ to $180^\circ$ phase shift with flat amplitude and phase responses over a very wide range of frequency can be obtained by adjusting the bias voltage $V_{b3}$ into the bottom DPMZM to alter the optical carrier phase, which is agreed with (4) given in Section 3. The measurements show only $\pm 1$ dB amplitude variation and $\pm 5^\circ$ phase deviation over the entire 2–40 GHz frequency range. It can be seen from Fig. 5 that the amount of amplitude variation and phase deviation increase when the RF signal frequencies above 40 GHz. This is mainly due to all the electrical cables and connectors used in the experiment had a 40 GHz bandwidth, and hence the RF signal had high loss at the frequencies above 40 GHz.

The wavelength sensitivity of the ultra-wide bandwidth photonic microwave phase shifter was investigated. This was done by changing the laser source wavelength by 0.08 nm from the desired value and measuring the phase shifter output amplitude and phase response as shown in the Fig. 6(a) and 6(b).
Fig. 6. Measured (a) amplitude and (b) phase response of the ultra-wide bandwidth photonic microwave phase shifter for different phase shifts when the laser wavelength was 0.08 nm away from the desired value. $V_{b2}$ was fixed at $-2.8$ V to maximize the optical carrier amplitude and $V_{b3}$ was varied from $-14.1$ V to $+14.2$ V to alter the optical carrier phase to realize $-180^\circ$ to $180^\circ$ RF signal phase shift.

Fig. 7. Measured (a) amplitude and (b) phase response of a conventional photonic microwave phase shifter implemented using only the optical filtering technique to realize SSB modulation. Measured (c) amplitude and (d) phase response of the same phase shifter when the laser wavelength was 0.08 nm away from the desired value. This shows the phase shifter amplitude and phase responses remain almost the same as that given in Fig. 5(a) and 5(b) for the system operating at the desired laser wavelength. Note that 0.08 nm away from the desired laser wavelength chosen to investigate the phase shifter wavelength sensitivity is due to the performance of the optical filter and the $90^\circ$ hybrid coupler used in the experiment. The optical filter had a roll-off factor of 280 dB/nm (2.24...
dB/GHz) and the 90° hybrid coupler had a 2 to 26.5 GHz operating frequency range. Therefore, in order for the upper DPMZM inside the dual-polarization DPMZM to operate as a SSB-SC modulator with 25 dB unwanted sideband suppression, the phase shifter laser wavelength tolerance is 0.12 nm. 0.08 nm instead of 0.12 nm was used in the experiment because the roll-off factor of the optical filter is smaller than 280 dB/nm at the beginning of the optical filter falling edge. It can be seen from Fig. 5(a) and 6(a) that the phase shifter has a slight frequency dependence characteristic. This is due to the limited controlling accuracy of the bias controller and the frequency dependent characteristic of the modulator and the 90° hybrid coupler, which generate a small unwanted sideband with amplitude dependent on the RF signal frequency. A conventional photonic microwave phase shifter, which only used the optical filtering technique to removing one RF modulation sideband, was set up in order to compare its wavelength sensitive performance with the ultra-wide bandwidth photonic microwave phase shifter. The laser source wavelength was optimized to maximize the phase shifter bandwidth. Figure 7 shows the corresponding measured phase shifter amplitude and phase response before and after 0.08 nm change in the laser wavelength from the desired value. A large change in both the amplitude and phase responses can be seen. The results clearly show the laser source wavelength needs to be critically controlled in order to obtain a stable output when using only the optical filtering technique for realizing SSB modulation in the conventional photonic microwave phase shifters.

Finally, the ultra-wide bandwidth phase shifter amplitude control function was demonstrated. This was done by altering the bias voltage \(V_{52}\) into the lower DPMZM so that one of the MZMs inside the lower DPMZM was biased away from the maximum transmission point. The phase shifter frequency response at 90° phase shift with different amount of output RF signal attenuation is shown in Fig. 8. This demonstrates the amplitude control function can be
realized by adjusting the bias voltage $V_{b2}$ into the bottom DPMZM to alter the optical carrier amplitude, which is agreed with (3) given in Section 3. It can be seen that the phase shifter amplitude and phase response remain flat for 15 dB changes in the output RF signal power. Since the phase shifter gain given in (5) is proportional to the output RF signal power, adjusting the bias voltage $V_{b2}$ or the laser power will change the phase shifter gain. This has been confirmed by experiments.

5. Conclusion

In conclusion, a new photonic microwave phase shifter has been experimentally demonstrated to realize a wide 2–40 GHz bandwidth phase shifting operation with a flat amplitude and phase response performance. The phase shifter is implemented using a 2–26.5 GHz bandwidth 90° hybrid coupler at the input of a dual-polarization DPMZM and an inexpensive optical filter to remove an unwanted RF modulation sideband over a very wide input RF signal frequency range. An RF signal phase shift is obtained by controlling a DC bias voltage into the dual-polarization DPMZM. The phase shifter also has the ability to control the RF signal amplitude via adjusting another modulator DC bias voltage. This is the first report on an experimental demonstration of a 2–40 GHz bandwidth photonic microwave phase shifter with amplitude control function. The proposed phase shifter can be used in RF and microwave phased arrays which have a wide range of applications including wireless base stations for mobile communications and radio astronomy [20]. It can also be used as the basis for a serrodyne system to apply a controlled frequency shift to a microwave signal [21].

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