Broadband photonic microwave phase shifter based on controlling two RF modulation sidebands via a Fourier-domain optical processor

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Abstract: An all-optical photonic microwave phase shifter that can realize a continuous 360° phase shift over a wide frequency range is presented. It is based on the new concept of controlling the amplitude and phase of the two RF modulation sidebands via a Fourier-domain optical processor. The operating frequency range of the phase shifter is largely increased compared to the previously reported Fourier-domain optical processor based phase shifter that uses only one RF modulation sideband. This is due to the extension of the lower RF operating frequency by designing the amplitude and phase of one of the RF modulation sidebands while the other sideband is designed to realize the required RF signal phase shift. The two-sideband amplitude-and-phase-control based photonic microwave phase shifter has a simple structure as it only requires a single laser source, a phase modulator, a Fourier-domain optical processor and a single photodetector. Investigation on the bandwidth limitation problem in the conventional Fourier-domain optical processor based phase shifter is presented. Comparisons between the measured phase shifter output RF amplitude and phase responses with theory, which show excellent agreement, are also presented for the first time. Experimental results demonstrate the full −180° to + 180° phase shift with little RF signal amplitude variation of less than 3 dB and with a phase deviation of less than 4° over a 7.5 GHz to 26.5 GHz frequency range, and the phase shifter exhibits a long term stable performance.

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References and links
10. S. Pan and Y. Zhang, “Tunable and wideband microwave photonic phase shifter based on a single-sideband
Microwave phase shifters are essential components in phased-array beamforming networks for radar and satellite communication systems [1, 2]. In such systems, the phase shifters need to provide full 0°-360° phase shift while having frequency-independent amplitude and phase responses. The output RF signal amplitude also needs to be fixed during the phase shifting operation. Multifunction radar and communication systems also require the phase shifters used in the phased-array antennas to operate in multi-frequency bands [3]. It is difficult for traditional electronic microwave phase shifters to operate over a very wide bandwidth. Photonic microwave signal processing techniques provide a promising solution to overcome this limitation. They also have the advantages of immunity to electromagnetic interference and compatible with fiber optic microwave systems [4–6]. Photonic microwave phase shifters implemented using different techniques such as stimulated Brillouin scattering (SBS) [7, 8], optical carrier and RF modulation sidebands amplitude and phase controls via a dual-parallel Mach-Zehnder modulator [9], a polarization modulator [10, 11], nonlinear optical loop mirrors [12], a wavelength tunable laser and a fiber Bragg grating [13], and an optical filter with a nonlinear phase response [14], have been reported.

A photonic microwave phase shifter implemented using a Fourier-domain optical processor (FD-OP) has also been proposed [15, 16]. It has the advantage of realizing multiple phase shifts in a single unit. However, the experimental results presented in [15] show the phase shifter has a frequency-dependent amplitude response. This limits its operating frequency range. Hence the phase shifter cannot be used in applications that cover multiple frequency bands. The reason of the frequency-dependent amplitude response and the phase shifter output RF signal amplitude changes during the phase shifting operation are not clearly explained in [15]. The authors only state the lower frequency limit of the phase shifter is due to the FD-OP resolution without simulation or experiment support. Also note that [16] only presents the phase response measurement of the FD-OP based phase shifter without showing the amplitude response, and until now there is no report on comparison between experimental results with theory for the FD-OP based phase shifter amplitude and phase responses.

In this paper, we not only provide detailed theoretical and experimental investigation on the frequency and phase-shift dependent characteristic in the conventional FD-OP based phase shifter but also provide a solution to extend the phase shifter operating frequency range to cover all the X, Kα, K, and Ka bands. The technique is based on controlling the amplitude and phase response profiles of the FD-OP to include the lower RF modulation sideband, which is eliminated in the conventional approach, in the phase shifter output. The novel FD-OP based photonic microwave phase shifter inherits all the advantages of the conventional structure while having a wider operating frequency range. It also has no bias drift problem since an optical phase modulator is used rather than an optical intensity modulator used in the conventional structure. Experimental results are presented that demonstrate a full 0°-360°
phase shift with little RF signal amplitude variation of less than 3 dB and a phase deviation of less than 4° over a 7.5 GHz to 26.5 GHz frequency range. The stability of the novel FD-OP based photonic microwave phase shifter is also experimentally measured for the first time.

2. Topology and principle of operation

The topology of the two-sideband amplitude-and-phase-control based photonic microwave phase shifter is shown in Fig. 1. The light from a continuous-wave laser source is phase modulated by an input RF signal and is launched into a FD-OP. The FD-OP is formed by a two-dimensional liquid crystal on silicon (LCoS), which can distribute the carrier and the sidebands of the phase modulated optical signal to different locations of the liquid crystal pixel based on their frequencies and control their amplitude and phase separately [17]. The RF phase modulated optical signal after Fourier-domain optical processing is detected by a photodetector. This generates an RF signal with the desired phase shift depending on the setting of the FD-OP. Note that the structure of the two-sideband amplitude-and-phase-control based photonic microwave phase shifter shown in Fig. 1 is the same as the conventional FD-OP based phase shifter [15, 16] except a phase modulator instead of an intensity modulator is used. The novelty of the phase shifter shown in Fig. 1 is not the structure but is the technique that extends the operating frequency range of the FD-OP based phase shifter.

The amplitude and phase response profiles of a commercially available FD-OP designed for the conventional FD-OP based phase shifter are shown in Fig. 2(a). It relies on the single sideband modulation scheme so the FD-OP is programmed to filter out one sideband, which is the left sideband, as shown in Fig. 2(a). The FD-OP is also programmed to realize an RF signal phase shift. This is done by introducing a phase difference in the FD-OP phase response at the carrier and the right sideband frequency, which can be seen in Fig. 2(a). Changing the phase difference, i.e. shifting the RF signal phase, can be obtained by changing the phase of either the carrier or the right sideband while leaving the other unchanged. The amplitudes of the carrier and the right sideband need to be fixed while shifting the RF signal in order to obtain an RF-phase-shift-independent amplitude response at the phase shifter output. Note that the commercial FD-OPs have a limited resolution of 10 GHz [18]. Since the edges of the FD-OP amplitude response profile have a finite slope, there is a residual left RF modulation sideband at the frequencies close to the carrier as shown in Fig. 2(a). Also note that there is a notch in the FD-OP amplitude response profile. The cause of the notch can be explained as follow. The LCoS in the FD-OP distributes the carrier and the right sideband to different locations of the liquid crystal pixel so that their phase can be controlled separately. This is equivalent to having a filter to select the carrier and program its phase, and another filter to select the right sideband and program the right sideband phase. The carrier and the right sideband with the specific phase are then combined at the FD-OP output. Since in practice the filter response edges have a finite slope, a notch is formed by placing two filter responses next to each other. This is the reason why a notch is appeared in the FD-OP amplitude response profile shown in Fig. 2(a). The frequency range where the notch appears in the FD-OP amplitude response profile corresponds to the optical phase change from one value to another. It was found that the notch depth in the FD-OP amplitude response profile increases with the increase of the phase response profile steepness. This notch alters the
amplitude of the right sideband at the frequencies close to the carrier. It can also be seen from Fig. 2(a) that there is a finite slope in the phase response when the phase is changed from one value to another. The notch in the FD-OP amplitude response and the finite slope in the FD-OP amplitude and phase responses alter the FD-OP based phase shifter output RF signal amplitude causing the phase shifter amplitude response to be frequency dependent and phase shift dependent. The experimental results presented in [15] show there are 2 dB RF signal amplitude variations in the 14 GHz to 20 GHz frequency range for a given phase shift and there are 4.5 dB changes in the RF signal amplitude when shifting the RF signal phase from 0° to 180° at 14 GHz. The changes in the phase shifter output RF signal amplitude are expected to increase as the RF signal frequency reduces. This limits the operating frequency range of the FD-OP based phase shifter. This problem can be overcome by using a very high resolution FD-OP with very steep response edges as shown in Fig. 2(b), to push the appearance of the unwanted notch in the FD-OP amplitude response and the residual left sideband to the frequencies very close to the carrier frequency. However, such FD-OP is currently unavailable.

![Amplitude and phase response profiles of (a) a commercially available FD-OP and (b) a FD-OP with a very high resolution and very steep edge response, together with the optical carrier and the modulation sidebands showing the operation principle of the conventional FD-OP based photonic microwave phase shifter.](image)
We solve the frequency-dependent and the phase-shift-dependent amplitude response problem to extend the operating frequency range of the FD-OP based phase shifter by programming the FD-OP to include the left sideband at the phase shifter output. This is shown in Fig. 3. Note that the frequency range of the left sideband to be included at the phase shifter output is from 0 GHz to around 20 GHz away from the optical carrier. The left sideband at the frequencies of more than 20 GHz away from the optical carrier is filtered out. This is because the experimental result in [15] shows the output RF signal amplitude response of the FD-OP based phase shifter is almost frequency independent at the frequencies above 20 GHz, and hence the left sideband at this frequency range is not required to compensate for the unwanted effect caused by the limited FD-OP resolution. Both the amplitude and phase response profiles of the FD-OP are programmed so that the amplitude and phase response of the phase shifter output RF signal formed by summing the two beating terms, which are formed by the right sideband beats with the carrier and the left sideband beats with the carrier, are as flat as possible over a wide frequency range for different phase shifts. The FD-OP amplitude response profile is programmed to fix the carrier and the right sideband amplitude while changing the phase difference between the carrier and the right sideband to realize an RF signal phase shift. The phase difference is introduced by designing the FD-OP phase response to fix the carrier phase to 0° and to alter the right sideband phase to the desired value. Figure 3 also shows the carrier and the two sidebands. Since an optical phase modulator is used for RF signal modulation, the two sidebands are in opposite phase.

3. Analysis and simulation results

This section provides detailed theoretical analysis and simulation results of the two-sideband amplitude-and-phase-control based photonic microwave phase shifter. With reference to the phase shifter structure shown in Fig. 1, when the optical phase modulator is driven by an RF signal with an angular frequency \( \omega_{RF} \), the electric field at the output of the optical phase modulator is given by

\[
E(t) = \sqrt{\frac{\pi}{\beta}} E_m \left[ J_0 \left( \beta \omega_{RF} \right) e^{i\omega_{0}t} + J_1 \left( \beta \omega_{RF} \right) e^{i\left(\omega_{0}t + \omega_{RF}t\right)} - J_1 \left( \beta \omega_{RF} \right) e^{i\left(\omega_{0}t - \omega_{RF}t\right)} \right]
\]

(1)

where \( E_m \) is the amplitude of the electric field at the input of the phase modulator, \( t_f \) is the phase modulator insertion loss, \( J_m(x) \) is the Bessel function of \( m^{th} \) order of first kind, \( \beta_{RF} = \frac{\pi V_{RF}}{V_s} \) is the modulation index, \( V_{RF} \) is the modulator input RF signal amplitude, \( V_s \) is the switching voltage of the optical phase modulator, \( \omega_{0} \) and \( \omega_{RF} \) are the optical carrier and input RF signal angular frequency respectively. As was mentioned in the last section that the FD-OP is programmed to realize the phase shifting operation by controlling the FD-OP phase.
response at the right sideband frequency and to realize a wide frequency-independent output RF signal amplitude and phase response by controlling the FD-OP amplitude and phase response at the left sideband frequency. The electric field at the output of the FD-OP can be written as

\[
E_{\text{out}}(t) = \sqrt{I} E_0 \left[ J_1(\beta_{\omega_R}) H(\omega) e^{i(\omega t + \phi_0)} + J_1(\beta_{\omega_L}) H(\omega + \omega_R) e^{i((\omega + \omega_R) t + \phi_0))} \right. \\
- J_1(\beta_{\omega_R}) H(\omega - \omega_R) e^{i((\omega - \omega_R) t + \phi_0))} \right]
\]  

(2)

where \(H(\omega)\) and \(\phi(\omega)\) are the amplitude and phase response of the FD-OP. The optical power into the photodetector at the RF signal frequency can be obtained by squaring the electric field at the output of the FD-OP and then collecting the terms containing the RF signal angular frequency \(\omega_{RF}\), and is given by

\[
P_{\text{out}} = 2\sqrt{I} P_{\text{in}} J_1(\beta_{\omega_{RF}}) J_1(\beta_{\omega_{RF}}) H(\omega) \left[ H(\omega + \omega_R) \cos(\omega_{\omega_R} t - \phi(\omega) + \phi(\omega + \omega_R)) \right. \\
+ H(\omega - \omega_R) \cos(\omega_{\omega_R} t + \phi(\omega) - \phi(\omega - \omega_R) - \pi) \right]
\]  

(3)

where \(P_{\text{in}}\) is the optical power at the input of the phase modulator. The output photocurrent at the RF signal angular frequency \(\omega_{RF}\) can be expressed as

\[
I_{\omega_{RF}} = 2\sqrt{I} P_{\text{in}} J_1(\beta_{\omega_{RF}}) J_1(\beta_{\omega_{RF}}) \sqrt{A^2 + B^2} \sin(\omega_{\omega_R} t + \tan^{-1}(B/A))
\]  

(4)

where \(A = H(\omega) \left[ H(\omega + \omega_R) \sin(\omega - \phi(\omega) - \phi(\omega + \omega_R)) + H(\omega - \omega_R) \sin(\omega - \phi(\omega) - \phi(\omega - \omega_R)) \right] \)  

(5)

\[
B = H(\omega) \left[ H(\omega + \omega_R) \cos(\omega - \phi(\omega) - \phi(\omega + \omega_R)) - H(\omega - \omega_R) \cos(\omega - \phi(\omega) - \phi(\omega - \omega_R)) \right]
\]  

(6)

Equations (4)-(6) show that the amplitude and phase of the output RF signal are dependent on the amplitude and phase response profiles of the FD-OP. The phase shifting operation is realized by programming the FD-OP response profiles via a computer connected to the FD-OP. The computer has a software called WaveManager for designing a WSP format file and loading the file into the FD-OP. This file contains four columns that are the frequency, attenuation, phase and port number columns. It has a frequency setting resolution of 1 GHz across the entire C + L band. The phase column of the WSP format file is designed so that the two beating terms, which are formed by the right sideband beats with the carrier and the left sideband beats with the carrier, are in phase at the low frequency range to increase the phase shifter output RF amplitude response level at low frequencies. The attenuation column of the WSP format file is designed to make the phase shifter output RF amplitude response to be as flat as possible over a wide frequency range. Once the attenuation and the phase columns in the WSP format file have been designed, the file is then loaded into the FD-OP. The light passed through the FD-OP with the desired amplitude and phase response profiles is routed out from one of the FD-OP output ports depending on the port number column setting in the WSP format file.

The conventional FD-OP based phase shifter output photocurrent at the RF signal angular frequency \(\omega_{RF}\) can be obtained by using the process as described above and is the same as (4) but \(A\) and \(B\) in this case are

\[
A = H(\omega) \left[ -H(\omega + \omega_R) \sin(\omega - \phi(\omega) + \pi/4) - H(\omega - \omega_R) \sin(\omega - \phi(\omega) - \pi/4) \right]
\]  

(7)

\[
B = H(\omega) \left[ H(\omega + \omega_R) \cos(\omega - \phi(\omega) + \pi/4) + H(\omega - \omega_R) \cos(\omega - \phi(\omega) - \pi/4) \right]
\]  

(8)
The amplitude and phase response profiles of the FD-OP for different output RF phase shifts in the conventional FD-OP based phase shifter are as shown in Fig. 4(a) and 4(b). Note that the profiles are obtained from the built-in simulation software mode of the FD-OP. By using the response profiles shown in Fig. 4(a) and 4(b) and together with Eqs. (4), (7) and (8), the output RF signal amplitude and phase responses of the conventional FD-OP based photonic microwave phase shifter are obtained as shown in Fig. 4(c) and 4(d). The responses in between the two dotted lines are agreed to the measured responses given in [15], which only shows the measurement in the frequency range of 14 - 20 GHz. It can be seen from Fig. 4 that the conventional FD-OP based phase shifter not only change the output RF signal amplitude during the phase shifting operation but also has a frequency-dependent amplitude response. The problem of the frequency-dependent amplitude response increases as the frequency reduces. Now we include the left sideband at the frequencies close to the optical carrier frequency of 193.4 THz, to the phase shifter output, and design the FD-OP amplitude and phase response profiles at the left sideband frequency as shown in Fig. 5(a) and 5(b). The amplitude and phase response profiles of the FD-OP are designed to reduce the variation in the output RF signal amplitude response. Note that the profiles shown in Fig. 5(a) and 5(b) are also obtained from the built-in simulation software mode of the FD-OP. Figure 5(c) and 5(d) shows the simulated phase shifter output RF signal amplitude and phase responses using the FD-OP response profiles shown in Fig. 5(a) and 5(b) together with Eqs. (4)-(6). It can be seen from Fig. 5(a) and 5(b) that the frequency range where the amplitude and phase responses are flat, is largely increased. There is < 3 dB amplitude variation for all phase shifts over the 7 to 40 GHz frequency range. The new technique extends the lowest operating frequency of the FD-OP based phase shifter from ~14 GHz down to ~7 GHz without using any extra component or having any penalty.

![Fig. 4. Simulated (a) amplitude and (b) phase response profile of the FD-OP designed for the conventional FD-OP based photonic microwave phase shifter, and corresponding simulated phase shifter output RF (c) amplitude and (d) phase response, for different phase shifts.](image-url)
The two-sideband amplitude-and-phase-control based photonic microwave phase shifter inherits all the advantages of the conventional FD-OP based phase shifter including simple structure, the ability to achieve multiple phase shifts by using the WDM technique, and simultaneous output RF signal amplitude and phase controls. Comparing with the conventional technique, the new technique uses an optical phase modulator for RF signal modulation rather than an optical intensity modulator, which has the advantage of not only bias free but also eliminate the bias drift problem. This improves the robustness of the FD-OP based phase shifter. Most importantly, it largely increases the operating frequency range that allows the phase shifter to operate from 7 GHz to the frequency only limited by the phase modulator bandwidth enabling the FD-OP based phase shifter to operate in a multi-band system.

4. Experimental results

Experiments were conducted with the setup shown in Fig. 6 to verify the principle of the two-sideband amplitude-and-phase-control based photonic microwave phase shifter. A tunable laser (ID PHOTONICS CDBX1), which operated at the C band and had a maximum output power of 16 dBm, was used as the optical source. The tunable laser frequency was 193.4 THz. The light from the laser source, passing through a polarization controller (PC), was launched into a 40 GHz bandwidth optical phase modulator (PHOTLINE MPZ-LN-40). The PC was used to align the light polarization state to maximize the efficiency of the phase modulator. It can be avoided by using a polarization maintaining fiber between the laser and the phase modulator. The RF phase modulated optical signal was processed by a FD-OP (Finisar...
WaveShaper 4000S), which had a resolution of 10 GHz. To the best of our knowledge, this FD-OP is the highest resolution FD-OP with both amplitude and phase control functions that is commercially available. The FD-OP was programmed to have the desired amplitude and phase response profiles to realize the frequency-independent and phase-shift-independent output RF signal amplitude and phase responses. Finally the Fourier domain optical processed phase modulated signal was detected by a 50 GHz bandwidth photodetector (u’t XPDV2120R), connected to a 26.5 GHz bandwidth vector network analyzer to display the amplitude and phase response of the output RF signal.

The frequency-dependent characteristic of the cables, the phase modulator and the photodetector were calibrated out. This was done by replacing the WaveShaper in Fig. 6 by a PC and a polarizer, and with proper adjustment of the PCs in front of the phase modulator and the polarizer to introduce amplitude imbalance in the two RF phase modulation sidebands so that the amplitude response of the phase modulation fiber optic link can be displayed and calibrated out by the network analyzer. The amplitude and phase response profiles of the FD-OP were programmed to be exactly the same as the ones used in the simulation, which are shown in Fig. 5(a) and 5(b). These FD-OP programmed response profiles were stored in the memory of the computer connected to the FD-OP. They were loaded from the memory one-by-one to obtain different RF signal phase shifts. The corresponding phase shifter output RF signal amplitude and phase responses were measured on the network analyzer and are shown in Fig. 7(a) and 7(b).

Fig. 7. Measured (a) amplitude and (b) phase response of the two-sideband amplitude-and-phase-control based photonic microwave phase shifter.
Note that the phase modulator was only used for RF signal modulation. No control in the phase modulator was required during the phase shifting operation. Comparison between the simulated and measured phase shifter output RF amplitude and phase responses for 0°, 90° and −90° phase shift are shown in Fig. 8. Excellent agreement between the simulation results and the experimental results can be seen. The experimental results demonstrated that the structure can realize a full phase shift range from −180° to +180° with < 3 dB amplitude variation and < 4° phase deviation over the 7.5 to 26.5 GHz frequency range. This is the first experimental demonstration showing the FD-OP based phase shifter has a measured 3-dB bandwidth of almost 20 GHz. The maximum measurement frequency was 26.5 GHz, which was limited by the bandwidth of the network analyzer. Compared with the measurements of the conventional FD-OP based phase shifter given in [15], the lowest RF operating frequency was extended from ~14 GHz to ~7.5 GHz. The amplitude and phase responses of the two-sideband amplitude-and-phase-control based photonic microwave phase shifter for the phase shifts other than the ones shown in Fig. 7 were measured by using different FD-OP amplitude and phase response profiles. The results show the phase shifter has frequency-independent amplitude and phase responses for different phase shifts over the 7.5 to 26.5 GHz frequency range.

Fig. 8. Simulated (dash) and measured (solid) amplitude and phase responses of the two-sideband amplitude-and-phase-control based photonic microwave phase shifter for (a) and (b) 0°, (c) and (d) 90°, and (e) and (f) −90° phase shift.

Stability is an important issue for the phase shifter to be used in practice. Until now, there are very few reports on the stability measurement of the photonic microwave phase shifter [19]. The FD-OP based phase shifter has a very simple structure compared to many reported phase shifters. Its performance does not depend on the light polarization state and is independent of changes in environmental condition. On the other hand, the phase shifters implemented using the SBS technique need careful control on the light polarization state into the SBS medium. Furthermore using a several kilometers long fiber as the SBS medium [7], [8] not only bulky but also requires temperature control on the system otherwise changes in temperature cause changes in the fiber length and consequently change the output RF signal phase. Compared to the conventional FD-OP based phase shifter, the phase shifter presented in this paper use an optical phase modulator rather than an optical intensity modulator which has the advantage of no bias drift problem. The two-sideband amplitude-and-phase-control based photonic microwave phase shifter can achieve a better stability performance compared to most reported photonic microwave phase shifter structures. The stability of the two-sideband amplitude-and-phase-control based phase shifter was investigated experimentally. This was done by measuring the phase shifter output amplitude and phase at the RF signal frequency.
frequency of 14 GHz over a period of time by setting the network analyzer sweeping time to be 17600 seconds. The experimental results are shown in Fig. 9. It can be seen that the amount of amplitude variation was less than 0.2 dB and the amount of phase deviation was less than 2° over the measurement period of almost 5 hours. This demonstrates that the two-sideband amplitude-and-phase-control based photonic microwave phase shifter has an excellent long term stability performance.

Fig. 9. Two-sideband amplitude-and-phase-control based photonic microwave phase shifter (a) amplitude and (b) phase stability measurement.

5. Conclusion

A photonic microwave phase shifter has been presented. It is based on the new operation principle that involves controlling the amplitude and phase of the two RF modulation sidebands. It has the ability of extending the phase shifter lower RF operating frequency, which results in a large increase in the operating frequency range compared to the conventional FD-OP based phase shifter that involves only one sideband. The robustness of the FD-OP based phase shifter has also been improved by using an optical phase modulator for RF signal modulation. Simulations have been conducted to investigate the bandwidth limitation problem in the conventional FD-OP based phase shifter and to verify the new technique can overcome this problem. Experimental results demonstrate that using the new two-sideband amplitude-and-phase-control technique in the FD-OP based photonic microwave phase shifter can increase the operating frequency range. The experimental results show the phase shifter can realize a full phase shift range from $-180^\circ$ to $+180^\circ$ with < 3 dB amplitude variation and < 4° phase deviation over the 7.5 to 26.5 GHz frequency range. The phase shifter stability measurement has also been presented. The results show the two-sideband amplitude-and-phase-control based phase shifter has < 0.2 dB amplitude variation and < 2° phase variation over the period of almost 5 hours.

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