Photonic generation of broadband RF phase shift with unbounded phase trajectory

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Abstract: A means of applying an adjustable RF phase shift over a broad band of frequencies is a requirement of diverse application. Photonic solutions to the generation of RF phase shifts have received significant attention for reasons of reduced cost, compactness and simplicity, yet the achievement of a phase shift extending beyond 360° range remains a challenge. The circuit architecture of a compact and broadband RF phase shifter with unbounded range based on two parallel DP-MZM architecture is presented and verified by simulation verification and emulated using off the shelf low frequency electronic components. Results demonstrate that the complex transmission of the phase shifter follows a trajectory that may encircle the origin an arbitrary number of times in either direction. The proposed architecture can be implemented using commercially available DP-QPSK modulator or can be integrated in any material platform that offers linear electro-optic phase modulators.

1. Introduction

A precise and broadband radio frequency (RF) phase shifter is needed in a variety of applications including phased array antenna systems to support high speed wireless communication and radar; and self interference cancellation (SIC) systems in a full duplex technology to improve the attainable spectral efficiency of a 5G network. The photonic generation of microwave phase shifts is receiving significant attention due to its simplicity, light weight, low cost, small size and broadband operation with minimal phase errors. The underlying principle is based on frequency shifting an optical carrier via single side band suppressed carrier (SSB-SC) modulation using RF carrier of interest followed by the re-insertion of a copy of the original optical carrier that is shifted in phase by a variety of means such as an optical phase modulator based on p-n junction devices; z-cut lithium niobate (LiNbO₃); or a polarization controller within a number of different circuit architectures [1-8].

In reference [1] an optical carrier is divided into two paths, one used to generate SSB-SC modulation, while the other path is phase shifted using an optical phase modulator. Both the paths are then combined on a photodiode to generate the phase shifted RF signal. A similar strategy to obtain the phase shift is followed in references [2-4] using a dual-polarization dual-parallel Mach Zehnder Modulator (DP-MZM); in which one DP-MZM generates the SSB-SC modulation while the other DP-MZM is kept unmodulated and arranged to provide a standard linear phase shift of the unmodulated carrier with limited range. The outputs of the both DP-MZM are then combined using a polarization beam combiner (PBC). The relative phase of the orthogonally polarised optical carrier and sideband is then adjusted by a polarization dependent optical phase shifter (OPS) [2] or a combination of polarization controller and polarizer [3-4]. A DP-MZM based scheme is presented in [5-8]. In [5], one child MZM is biased at the minimum transmission point (MITP) and driven by an RF signal, thereby generating double sideband suppressed carrier (DSB-SC) modulation; while the other child MZM is biased at the MATP to pass the carrier. The two outputs are combined by using an optical coupler [6]. The optical phase shift is applied by tuning the phase adjust voltage of the parent MZM. Finally, an optical bandpass filter (OBF) is used to suppress one of the sidebands. A similar method is described in [6] except the combining is done through a PBC and the optical phase shift is implemented using polarization dependent OPS. Reference [7] describes a DP-MZM based scheme capable of a 360°-degree phase shift founded on the precise settings of the phase and amplitude of the optical carrier and two sidebands using predetermined modulator bias voltages. An architecture consisting of, two parallel MZM driven by in-phase and quadrature phase RF signal modulate orthogonally polarised optical carriers combined on a photodiode is demonstrated in [8]. The slope about the operating point of the two MZM is varied by adjustment of their respective DC bias voltage, thereby the sign and magnitude of the in-phase and quadrature phase modulation components is adjusted resulting in the phase shift of the superimposed components. For proper operation of the scheme, the modulation depth should be small which leads to high insertion loss and careful adjustment of the two bias voltages is required as, for a constant magnitude RF output, both bias voltages depend on the desired phase shift. A photonic integrated phase shifter based on silicon-on-insulator technology is presented in [9]. A single side band (SSB) full carrier modulation is generated using a DP-MZM. An optical deinterleaver filter is used to separate the optical carrier and the sideband. The phase of the isolated carrier is then shifted by using a p-n junction based optical phase shifter and combined with the sideband on a photodiode. All

these methods require either an optical deinterleaver filter or optical bandpass filter, precise control of the polarization and/or polarizer, bias voltages or suffers from lack of phase shift linearity and range. Moreover, the need for a continuous phase shift range extending beyond 360° degree is gaining appreciation. For an example, improved robustness to loss of lock of an optoelectronic oscillator has been demonstrated by enlarging the RF tuning phase shift ranges from 350° degrees to 1160° degree using a frequency conversion pair [10].

In this paper, a circuit architecture is proposed based on a parallel pair of dual-parallel Mach-Zehnder modulators (DP-MZM) that requires no additional control or filter for proper operation. Furthermore, the linearity of the phase shifter remains valid for a wide range of frequencies. The proposed phase shifter can generate any phase without bound. The complex transmission of the phase shifter follows a trajectory in the complex plane that may encircle the origin an arbitrary number of times in either direction. The practical implementation of the proposed design can be demonstrated using a commercially available dual polarization quadrature phase shift keying (DP-QPSK) modulator. Due to unavailability of a-QPSK modulator, experimental verification by an electronic emulation of the proposed concept is presented using off the shelf components.

2. Principal of operation

The circuit diagram of the proposed broadband phase shifter is given in fig. 1. The circuit consists of two DP-MZM. The upper DP-MZM generates the suppressed carrier-single side band modulation of the applied RF drive signal. To obtain this function, the bias of the two parallel child MZM is set to their minimum transmission points (MITP), while the mother MZM is set to its quadrature transmission point (QTP). Then the in-phase (I) and quadrature-phase (Q) of the RF drive signal is applied to the upper and lower child MZM respectively [11]. SSB-SC modulation can also be regarded as the shifting of the optical carrier frequency by an amount equal to the RF frequency. The bias of the lower DP-MZM is set similarly to the upper DP-MZM, i.e the two parallel MZM is set to MITP or null transmission point and the mother MZM is set to QTP. A static or low frequency in-phase and quadrature-phase signal is applied to the two child MZM to shift the phase of the optical carrier. When the output of the two DP-MZM imping on a photodiode, a phase shifted version of the RF drive signal is recovered.

Fig. 1. (a) Schematic diagram of the proposed broadband phase shifter; (b) phase shift trajectory (either clockwise or anti-clockwise); LD, Laser diode; SSB, Single side band; PD, Photodiode.

In the small modulation index (m_1) approximation, the transmission [11] of the upper DP-MZM is

$$T_{upper\ DP-MZM} = (1/4) m_1 \exp(i(\omega_c \pm \omega_{rf})t) \quad (1)$$

where, ω_c and ω_{rf} is the optical and RF carrier frequency. Depending on the phase lead-lag between upper MZM and lower MZM, either an upper SSB-SC or lower SSB-SC modulation is obtained. Alternatively, one output port generates either upper/lower SSB-SC modulation while the other output port generates the complementary SSB-SC modulation for a two-output port DP-MZM [12]. The modulation index m_1 is defined by:

$$m_1 = \pi v_{RF} / v_\pi \quad (2)$$

where, v_{RF} is the amplitude of the applied RF signal and v_π is the half-wave voltage of the phase modulator used to form the MZM. Similar way, the output transmission of the lower DP-MZM can be written:

$$T_{\text{Lower DP-MZM}} = (1/4) m_2 \exp(i(\omega_c t \pm \varphi)) \quad (3)$$

where φ is the applied phase shift to the optical carrier through I-Q modulation at the lower DP-MZM. The modulation index m_2 can be written as:

$$m_2 = \pi v_p / v_\pi \quad \text{where} \quad v_p = \sqrt{v_I^2 + v_Q^2}$$

The v_π here may be different than for m_1 due to the difference in the frequency of the RF modulation and the IQ controls. The output of the upper DP-MZM and lower DP-MZM is combined and impinged to a photodiode. Finally, the beat signal of interest at the output of the photodiode is,

$$\propto \cos(\omega_{rf} t \mp \varphi) \quad (4)$$

The phase shift φ of the RF signal given by Eq. (4) may be continuously varied by a continuous variation of the bounded I and Q bias at the lower DP-MZM. The small modulation index m_1 is a non-necessary condition. Jacobi Anger expansion leads to same solution while providing details on the amplitude of the Bessel sidebands [13].

Rather than applying the IQ RF and IQ bias separately to a parallel pair of IQ modulators, the vector sum of the IQ RF drive and IQ bias may be applied to a single IQ modulator to obtain the same result to the extent that an IQ modulator has a transmission is linear with respect to the IQ vector. Consequently, a single DP-MZM can be used to perform a similar operation [14]. However, without special linearization [15] measures the single DP-MZM arrangement is limited to small modulation indices m_1, m_2 resulting in high insertion loss compared to the parallel DP-MZM solution.

3. Simulation verification & experimental result

Circuit simulation using VPIphotonics is performed to verify the theoretical prediction. A Distributed Feedback (DFB) laser having wavelength of 1550 nm and an output power of 10 dBm is used as the optical source. The insertion loss and extinction ratio of each MZM is set to be 4 dB and 30 dB respectively. The half-wave voltage of each MZM is set to 5 V. The in-phase and quadrature phase of the RF drive signal with peak amplitude of 1.2 V and a frequency of 10 GHz is applied to the upper DP-MZM. This results in a frequency shift of the optical carrier by an amount of 10 GHz. Although suppressed-carrier modulation is desired, the suppression is not complete due to the finite extinction of the MZM. For the purpose of demonstrating the operating principle by simulation, a very low frequency cosine- and sine-waveform are applied to the in-phase and quadrature-phase inputs to the lower DP-MZM to generate a slow linear ramp of the optical carrier phase. Once both the output of the upper and lower DP-MZM are combined at the photodiode, the desired phase shifted RF carrier can be observed.

Figure 2 shows the phase shift at different static phase (φ) of the low frequency drive signal predicted by the simulation. The output phase shift exactly matches the applied phase shift and without bound. The corresponding phasor can rotate about the origin of the complex plane in either direction (clockwise or anti-clockwise) an arbitrary number of times. The power variation of the recovered signal at different phase shifts is found to be ~ 1.8 dB maximum. This variation is the result of the nonlinear transmission function of the DP-MZM and may be corrected by pre-distortion of the in-phase and quadrature phase controls of the lower DP-MZM or by application of alternative methods [15] of the lower DP-MZM. The proposed circuit can be used up to the bandwidth of the phase modulators used to

Fig. 2. Simulated phase relationship between the input and output RF signal.

form the DP-MZM. The practical implementation of the proposed circuit can be realized by commercially available dual polarization quadrature phase shift keying (DP-QPSK) modulator. Hybrid integration of silica and modulator based on LiNbO₃ can be used to verify the concept [16].

Due to unavailability of a DP-QPSK-modulator and vector network analyzer, the concept is verified experimentally using off the shelf lower frequency electronic components. Figure 3 shows the schematic diagram of the experimental setup. An Analog Devices HMC630 used as vector modulator to emulate the function of a DP-MZM. The vector modulator has one input port, one output port and two other input ports for the application of I and Q controls. The operating frequency range is 700-1000 MHz, whereas the 3dB bandwidth of the I and Q ports are 180 MHz. A Minicircuits ADP-2-10W (5 to 1000 MHz) is used as the input power splitter. To emulate the function of a photodiode, a double balanced mixer (ADE-2+) from Minicircuits is used. A RF signal with a frequency of 800 MHz and 10.5 dBm output power is used as the input carrier. A Rohde & Schwarz SMB 100A signal generator is used as the RF LO. An IF signal having frequency of 115 MHz is applied to a 90° hybrid (Minicircuits ADQ-22+) to generate the in-phase and quadrature-phase components. The in-phase and quadrature-phase component is then applied to the I and Q ports respectively of the upper vector modulator.

Figure 3(b) shows the measured electrical spectrum of the SSB-SC modulation generated at a frequency 915 MHz. The sideband (at 915 MHz) to carrier (at 800 MHz) suppression ratio is 15 dB. In an optical implementation, the RF LO is replaced by an optical carrier and the IF signal is by RF signal that is needed to be phase shifted. In optics, a

Fig. 3. (a) Schematic of the experimental setup; (b) and (c) are the measured spectra (electrical) of the signal at point (b) and (c) in schematic (a); IF, intermediate frequency; LO, local oscillator; VM, vector modulator; DC, direct current. An electrical resolution bandwidth of 1 kHz is used to capture the data.

sideband to carrier suppression ratio of ~20-22 dB was reported experimentally using a DP-MZM architecture [12-13] a decade ago. A suppression of ~40 dB is obtained [16] using a phase shifter and/or variable optical attenuator (VOA) as a trimming means. The phase of the carrier that passes through the lower vector modulator is adjusted by applying a DC voltage in the range of 0.5 V to 2.5 V to the I and Q port of the lower vector modulator using a precision DC source (Agilent B2912A). To adhere the specified ranges, the applied I and Q voltages are defined by:

$$I = 1.5 + \cos(\varphi) \quad (5)$$

$$Q = 1.5 + \sin(\varphi) \quad (6)$$

Fig. 4. Screen image of the oscilloscope showing the phase difference between the generated RF signal and a reference signal for various target phase shift as input; (a) target phase shift 0° ; (b) target phase shift 45° ; (c) target phase shift 90° and (d) 135° respectively.

A phase ramp is applied to the carrier by changing the value of φ , results in equal amount of phase shift at the recovered IF signal at the output of the mixer. Figure 3(c) shows the electrical spectrum of the measured carrier for a particular combination of I and Q values. A similar length of semi rigid RF cable is used to connect the two vector modulators with the double balanced mixer, making sure that the path lengths remain same. In a photonic integrated circuit, this can easily be achieved. The output of the mixer is then passed through a low pass filter (LPF) to the digital storage oscilloscope. Since, there is no vector network analyzer (VNA), the length of connection between the LPF and oscilloscope is kept to a minimum so that the actual phase at the output of the LPF is measured by the oscilloscope. Nevertheless, an error of $\sim 2\text{-}3^\circ$ is added due to the different path lengths. Figure 4 and 5 shows the screen image of

Table 1. Experimental details of the applied input voltage (target phase), measured phase, actual phase shift and peak to peak voltage of the recovered IF signal.

Input voltage (volts)		Target phase degree	Phase shift with respect to reference signal (degree)	Adjusted phase (degree)	Actual phase shift (degree)	Amplitude $V_{peak-peak}$ (mV)
I-port	Q-port					
2.5	1.5	0	170	$170 - 170 = 0$	0	110
2.406	1.922	25	-170	$-170 - 170 = -340$	20	111
2.207	2.207	45	-150	$-150 - 170 = -320$	40	113
1.5	2.5	90	-100	$-100 - 170 = -270$	90	114
0.793	2.207	135	-60	$-60 - 170 = -230$	130	114
0.5	1.5	180	-19	$-19 - 170 = -189$	171	112
0.633	1.0	210	10	$10 - 170 = -160$	200	110
0.793	0.793	225	29	$29 - 170 = -141$	219	109
1	0.633	245	50	$50 - 170 = -120$	240	110
1.5	0.5	270	80	$80 - 170 = -90$	270	112
2.207	0.793	315	120	$120 - 170 = -50$	310	110
2.406	1.077	335	140	$140 - 170 = -30$	330	110

Fig. 5. Screen image of the oscilloscope showing the phase difference between the generated RF signal and a reference signal for various target phase shift as input; (a) target phase shift 180° ; (b) target phase shift 225° ; (c) target phase shift 270° and (d) 315° respectively.

the measured phase difference between the recovered IF signal and the reference signal for various input phase values φ . The measured phase difference is then adjusted by subtracting an equal amount of phase shift from all the measured phase to obtain the actual phase shift. Table 1 shows the details of applied voltage to the I and Q port, measured phase difference and actual phase shift. Figure 6. (a) plots the measured phase shift as a function of applied phase shift (target phase shift). A straight line is obtained using curve fitting which also justify the theoretical prediction. A very small error is obtained between the target phase shift and actual phase shift. In some cases, the measured phase shift is identical to the target shift. Measurement results also verify that the peak to peak amplitude of the recovered IF signal remain almost constant. Figure 6. (b) shows the comparison between expected I-Q values and measured I-Q values. A maximum error of 9-10° degree is obtained for two cases. However, the phase measurement using a VNA will certainly improve the precision of the measurement. Nevertheless, a 360° -degree rotation is obtained experimentally.

Fig. 6. (a) Relationship between target and measured phase shift; (b) measured I-Q value versus expected I-Q value.

The phase trajectory can rotate on the unit circle either way (clockwise or anti clockwise) indefinite amount of times.

4. Conclusion

In summary, a novel photonic technique for obtaining the phase shift of a RF signal is reported with simulation verification. The proposed circuit can function for a wide range of frequencies and it can generate a phase without bound. The circuit may be implemented in practice using a commercially available DP-QPSK modulator. The bandwidth of the operation depends on the bandwidth of the phase modulators that forms the MZM. An experimental verification of the concept is presented using off the shelf low frequency electronics. Results show that a RF phase shift of 360° degree or more can be obtained with negligible penalty at the amplitude of the phase shifted signal. Results also show that an SSB-SC modulation having sideband to carrier suppression ratio of only 15 dB or more is good enough for the proposed architecture to function correctly

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Disclosures

The authors declare no conflicts of interest.

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