A novel linear photonic RF phase shifter base on polarization controller

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Abstract *A novel linear photonic RF phase shifter base on polarization controller is presented and the theoretical fundamentals of the design are explained. A prototype of the phase shifter with 26.75GHz bandwidth and 360 degrees tuning range is experimentally demonstrated.*

Introduction

Recently, phased-array and smart antennas play an important role in electronic warfare systems and broadband wireless access networks, and the interests in applying the photonic technology to phased-array antennas are increasing. Compared with those conventional phased-array antennas based on purely electrical devices, optically fed phased-array antennas have the advantages in the broader bandwidth, smaller power consumption, lower weight, and better performance in EMI. Photonic radio frequency (RF) phase shifter is one of the most important components of such an integrated photonic approach, which provide an accurate and easily controllable phase shift to the RF signal for antenna beam forming.

Various architectures for constructing photonic RF phase shifters have been realized on homodyne mixing techniques [1], vector sum techniques [2] and nonlinear effects [3]. In this letter, we introduce a novel linear photonic phase shifter based on a half-quarter-quarter (HQQ) wave plates (WP) polarization controller (PC). Compared with those previous designs, this scheme decreases the signals crosstalk by using a single commercial modulator instead of complex integrated planar devices applied in designs [1]; this scheme avoids amplitude modulation of the RF signals in designs [2], which is not desired in practical phased-array antenna systems; and this scheme reduces the capability requirement of devices, for example, a stable and high power pump source demanded in designs [3], which are complex and costly for practical implementation. The theoretical fundamentals of this scheme are explained and a prototype with 26.75GHz bandwidth is experimentally demonstrated. The bandwidth of this phase shifter is just limited by the bandwidth of the optical transmitter and receivers deployed, and it provides a linear phase shifter that can be continuously tuned in a range greater than 360°.

Experimental setup

The scheme used to experimentally demonstrate the photonic phase shifter based on PC is outlined in Fig.1, which consists of two modules: orthogonal polarization signal generator and RF phase shifter.

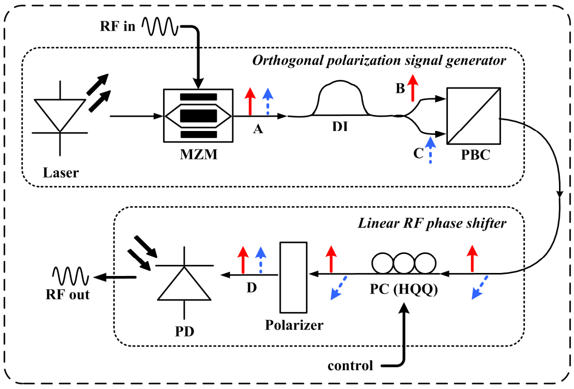

Fig. 1. Experimental setup

The optimal method to generate an orthogonal polarization optical signal is locking two lasers; the wavelength difference between the two lasers is the frequency of the target RF signal. However, limited by the experiment condition, we produce an orthogonal polarization optical signal by generating an optical carrier-suppressed (CS) signal using single Mach-Zehnder modulators (MZM). The RF signal is pre-amplified to the switching voltage V_π and the MZM is biased at the transmission null point. The output of a 1553nm DFB laser is modulated a 13.375GHz RF signal using MZM. The CS signal is generated and its optical spectra present two phase-locked carriers, which are 26.75GHz apart. The CS signal is coupled into a DI (FSR=53.5GHz). By adjusting the differential phase between the two arms of DI, the CS signal is filtered and the two phase-locked carriers are demultiplexed. Polarization beam combiner (PBC) combines the separate optical carriers into a single orthogonal polarization signal and sends to the linear RF phase shifter.

The linear RF phase shifter is composed of PC, polarizer and photo detector (PD). The orthogonal polarization signal obtains a relative phase difference by adjusting the rotation angle of WP in a HQQ type PC, which consist of a rotatable half-WP (HWP), a rotatable quarter-WP (QWP) and a stationary QWP. And the phase shifted orthogonal polarization signal is sent to a polarizer, which is set at 45° and forces interference between the two orthogonal polarization components. Then, the output signal from polarizer is detected by a 50GHz photo detector and amplified. The achieved RF signal is the controllable phase-shifted signal by the rotation angle of the PC.

Principle

Assume the plane wave propagates along the *z*-axis; the polarization of the wave is governed by the electric-field evolution in the *xy*Basis plane. For convenience of notion but without loss of generality, the optical field at the CS transmitter when it is driven by a half-rate RF signal is given by E_{CS},

$$E_{CS}(\hat{x},\hat{y},t)=\hat{x}\cdot\left[A_1\exp j\pi t\left(2f_c-f_{RF}\right)+A_2\exp j\pi t\left(2f_c+f_{RF}\right)\right] \quad (1)$$

where A_1 and A_2 are the amplitudes of the two phase-locked carriers, respectively; f_c and f_{RF} are the frequencies of the optical carrier and the RF signal, respectively; *x,y* are the orthogonal polarization directions, respectively; and *t* is the time. The optical CS signal is filtered by the DI and sent to the PBC, where the two separate optical carriers are combined into the single orthogonal polarization signal E_{PBC},

$$E_{PBC}(\hat{x},\hat{y},t)=\hat{x}\cdot A_1\exp j\pi t\left(2f_c-f_{RF}\right)+\hat{y}\cdot A_2\exp j\pi t\left(2f_c+f_{RF}\right) \quad (2)$$

Then, signal E_{PBC} goes through the PC and the two orthogonal polarization components acquire different shifting phases. To explain the action of the PC mathematically, the Jones polarisation matrix calculus, which can describe passive optical components like the HWP and QWP using a four-element transformation matrix $J_{WP}(\varphi,\theta)$,

$$J_{WP}(\varphi,\theta)=\begin{pmatrix}\cos\frac{\varphi}{2}+j\sin\frac{\varphi}{2}\cos2\theta & -j\sin\frac{\varphi}{2}\sin2\theta\\ -j\sin\frac{\varphi}{2}\sin2\theta & \cos\frac{\varphi}{2}-j\sin\frac{\varphi}{2}\cos2\theta\end{pmatrix} \quad (3)$$

where θ is the rotation angle to the *y* axis in a clockwise direction, and $\varphi=\pi$ for a HWP, $\varphi=\pi/2$ for a QWP. For a particular acquired different shifting phase ϕ between the two orthogonal polarization components, let the HWP be rotated by $\phi/4$ to the *y* axis in a clockwise direction such that $\theta=\pi/2-\phi/4$, let the first QWP be rotated in the same direction through twice the rotation angle of the HWP such that its fast axis makes an angle $\theta=3\pi/4-\phi/2$ to the x axis, and let the second stationary QWP be tilted with its fast axis at $\theta=-\pi/4$ to the x axis. The complex vector electric field for the HQQ type PC can be expressed as M_{HQQ},

$$M_{HQQ}=J_{WP}\left(\pi,\frac{\pi}{2}-\frac{\phi}{4}\right)\cdot J_{WP}\left(\frac{\pi}{2},\frac{3\pi}{4}-\frac{\phi}{2}\right)\cdot J_{WP}\left(\frac{\pi}{2},-\frac{\pi}{4}\right)=\begin{pmatrix}e^{j\frac{\phi}{2}} & 0\\ 0 & e^{-j\frac{\phi}{2}}\end{pmatrix} \quad (4)$$

From this, it can be seen that any phase shift between 0 and 2π is continuously controllable by rotating the WP in a HQQ type PC, and the amplitude of the input light is not affected by this action. The signal at the output of PC is given by E_{PC}, and the phase-shifted orthogonal polarization signal is sent to the 45° polarizer and the two orthogonal polarization components interfere. The optical field signal at the output of polarizer is given by E_P,

$$E_{PC}(\hat{x},\hat{y},t)=\hat{x}\cdot A_1\exp j\left[\pi t\left(2f_c-f_{RF}\right)+\frac{\phi}{2}\right]+\hat{y}\cdot A_2\exp j\left[\pi t\left(2f_c+f_{RF}\right)-\frac{\phi}{2}\right] \quad (5)$$

$$E_P(\hat{x},\hat{y},t)=\hat{x}\cdot\frac{1}{\sqrt{2}}\left\{A_1\exp j\left[\pi t\left(2f_c-f_{RF}\right)+\frac{\phi}{2}\right]+A_2\exp j\left[\pi t\left(2f_c+f_{RF}\right)-\frac{\phi}{2}\right]\right\} \quad (6)$$

Finally, the output signal from polarizer is detected using the 50GHz PD, and the *AC* part of the output current from the PD is given by I_{PD},

$$I_{PD}(t)=RA_1A_2\cdot\cos(2\pi f_{RF}t+\phi) \quad (7)$$

where *R* is the responsivity of the PD. Therefore, the controllable shifted phases of the two optical carriers are directly translated to the phase of the RF signal.

Results and discussions

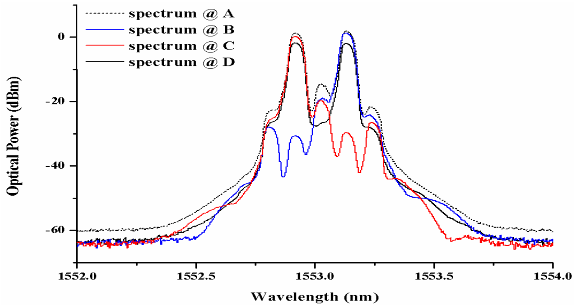

Fig. 2. Measured optical spectrum

Fig.2 shows the measured optical spectrum at the corresponding points A, B, C and D in Fig.1. Curve A is the spectrum of the generated CS signal, curves B and C are the spectrums of the two demultiplexed phase-locked carriers and curve D is the spectrum of the phase-shifted CS signal.

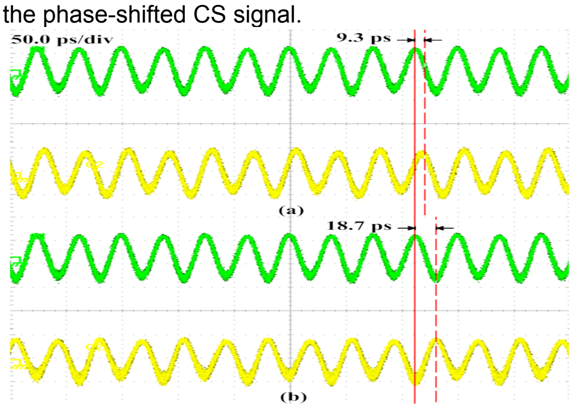

Fig. 3. Measured $\pi/2$ and π radian phase shifting

Fig.3 shows the results of experimental verification, the lower curves in sub figures (a) and (b) illustrate the $\pi/2$ and π phase-shifted RF signals respectively, and the upper curves in sub figures (a) and (b) are the RF signals without phase shifting for comparison.

Conclusions

In this paper, a RF photonic phase shifter based on PC is realized and the theoretical fundamentals of this scheme are analyzed. A prototype with 26.75GHz bandwidth is experimentally demonstrated and a near-linear 360° phase-shift tuning range is achieved.

References

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