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A Millimeter-Wave Photonic Vector-Sum Phase Shifter Using Polarization Maintaining Fiber

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Abstract

We propose and demonstrate a novel photonic vector-sum phase shifter that, using two pieces of polarization maintaining fiber, provide continuous and full phase shift up to 2π at the millimeter-wave frequency of 30.48GHz.

I. Introduction

Recently, optically controlled phased array antennas (PAAs) are attracting many research efforts due to their advantages such as low loss, light weight, broad bandwidth, and high flexibility, compared with electrically controlled systems [1]. A photonic phase shifter that can control RF phase easily and accurately in optical domain can be a key component in optically controlled PAA systems

Until now, photonic phase shifters are realized based on heterodyne mixing technique [2-4] or vector-sum technique [1,5]. In the heterodyne mixing technique, two optical modes having different optical frequencies and optical phases are generated and detected by a photo detector. The phase difference between them is controlled by a $LiNbO_3$ modulator [2] or polymer modulators [3,4]. In this method, optical phase difference results in phase shift in RF domain.

In the vector-sum technique, two sinusoidal signals having same frequency but different amplitudes and phases are summed. The phase of the resulting signal can be controlled by changing amplitudes of two signals. In previously reported photonic vector-sum phase shifters, several modulators [1] or variable attenuators and optical delay lines [5] are required resulting in limited practicality.

In this paper, a new photonic phase shifter based on vector-sum technique is proposed and demonstrated using polarization maintaining fiber (PMF).

II. Theory

The following equation shows the principle of vector-sum method.

$$A_1\sin(\omega t) + A_2\sin(\omega t + \Delta\varphi) = A\sin(\omega t + \varphi)$$

$$,\text{where} \quad A = \sqrt{A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\varphi)}$$

$$\varphi = \tan^{-1}\left(\frac{\sin(\Delta\varphi)}{A_1/A_2 + \cos(\Delta\varphi)}\right)$$

As shown in the above equation, the phase of the resulting signal is determined by the amplitude ratio

(A_1/A_2) with the fixed value of $\Delta\varphi$. Therefore, to realize the photonic vector-sum phase shifter, two optical sinusoidal signals whose amplitudes can be controlled with the fixed phase difference are required.

Fig.1 shows a new configuration to realize above scheme. As shown in the figure, the laser output signal is intensity-modulated by an electro-optic modulator and fed into either upper or lower PMF selected by an optical switch. The output optical intensity of the modulator is given by

$$\frac{I}{2}[1-\cos(\frac{\pi}{V_\pi}(V_m\sin(\omega t)+V))] \qquad (2)$$

where ω is the modulated frequency, V_m is the RF zero-to-peak voltage, V is the bias voltage applied to the modulator electrode, V_π is the voltage required to produce π phase shift in modulator output and I is optical intensity into the modulator.

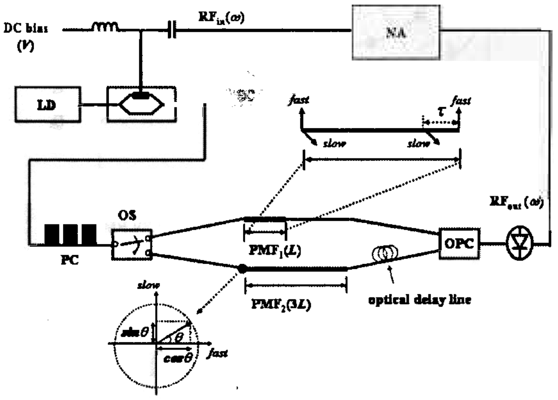


Fig. 1. Configuration and measurement set-up for the proposed photonic phase shifter. PC: polarization controller, OS: optical switch, OPC: optical power combiner, PMF: polarization maintaining fiber, NA: network analyzer.

When the modulated signal is injected to PMF, the power of the signal is transferred to two orthogonal polarization modes, fast and slow. The coupled power ratio between two modes is determined by the incident polarization state controlled by a polarization controller. If the angle between fast axis and input polarization is θ ($0°\leq\theta\leq90°$), the power coupled to fast and slow mode is proportional to $cos^2\theta$ and $sin^2\theta$, respectively.

At the end of PMF, the two modes arrive at different time due to PMF Differential Group Delay (DGD). At the photodetector, these two modes produce summation of two electrical signals having a phase difference determined by the PMF length and DGD. The resulting photocurrent having the modulation frequency component is given as:

$$I_C \propto J_1(\frac{\pi V_m}{V_\pi})I\sin(\frac{\pi V}{V_\pi})(\cos^2(\theta)\sin(\omega t) + \sin^2(\theta)\sin(\omega t+\omega\tau)) = A\sin(\omega t+\varphi) \qquad (3)$$

where

$$A = J_1(\frac{\pi V_m}{V_\pi})I\sin(\frac{\pi V}{V_\pi})\sqrt{1+\frac{1}{2}\sin^2 2\theta(\cos(\omega\tau)-1)}$$

and $\varphi = \tan^{-1}(\dfrac{\sin^2\theta\sin(\omega\tau)}{\cos^2\theta+\sin^2\theta\cos(\omega\tau)})$

In (3), the phase of the signal generated by the fast mode is assumed zero for setting a reference. As can be seen from the above equation, by changing θ from 0 to $\pi/2$, φ is tuned from 0 to $\omega\tau$ when $\omega\tau<\pi$ or from π to $\omega\tau-\pi$ when $\omega\tau>\pi$. If the value of $\omega\tau$ is set to $\pi/2$ by fixing the length L of PMF (PMF$_1$) for a given RF frequency, φ can be tuned from 0 to $\pi/2$. If the value of $\omega\tau$ is set to $3\pi/2$ by using another piece of PMF having length of $3L$ (PMF$_2$), above relation tells that φ can be tuned from π to $\pi/2$. However, this does not include the additional phase shift due to the length difference between two pieces of PMF. In order to explain this additional phase shift, Eq. (3) for PMF$_2$ can be modified as below:

$$I_C \propto J_1(\frac{\pi V_m}{V_\pi})I\sin(\frac{\pi V}{V_\pi})(\cos^2(\theta)\sin(\omega t+\delta)+ \sin^2(\theta)\sin(\omega t+\omega\tau+\delta)) = A\sin(\omega t+\delta+\varphi) \quad (4)$$

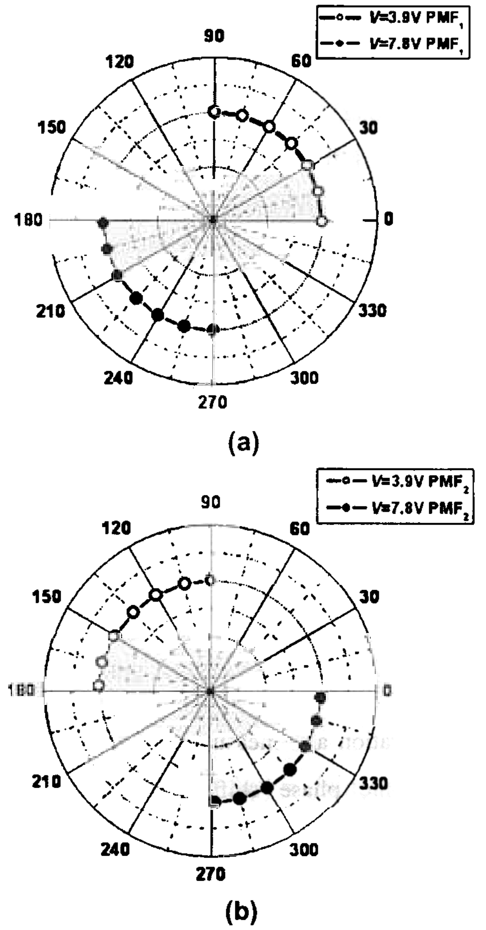
where δ is introduced to account for the phase shift due to the length difference of PMF_1 and PMF_2. δ is given as $\delta = \omega(3L-L)n/c$, where c is light velocity and n is refractive index of the fast mode because our reference phase is taken with respect to the fast mode. With this, φ tuning range is from $\pi + \delta$ to $\pi/2 + \delta$. Consequently, the range from $\pi/2$ to $\pi/2 + \delta$ can not be covered by using two pieces of PMF. In order to solve this problem, a fixed delay line that makes $\delta = 2m\pi$ (m: integer) is inserted after PMF_2. With this configuration, change of θ from 0 to $\pi/2$ can produce RF phase shift from 0 to π with two pieces of PMF.

The RF phase shift from π to 2π can be easily achieved by changing the modulator bias voltage by the amount of V_π, since this produces the reversal of the sign of detected RF signal. In short, by controlling the polarization state of input light into two pieces of PMF having required lengths and using two modulator bias voltages separated by V_π, the full range of phase shift from 0 to 2π can be achieved.

As shown in Eq. (3), the amplitude (A) is also a function of θ, causing amplitude variation as phase is shifted. This is an undesired effect but the amount of variation is at most 3dB as is experimentally confirmed later.

III. Experiment and Results

With an experimental set-up shown in the Fig. 1, RF phases of photo-detected signals were measured by a network analyzer as the polarization state of light injected into two separate pieces of PMF was varied. The DGD value of commercially available PMF was experimentally measured from the first dip position in the PMF frequency response [6] and found to be 0.70ps/m. At 30GHz, the required PMF length L is 11.7m and two pieces of PMF having length of L and $3L$ with standard fiber connectors were made. There were, however, errors due to uncertainties in estimated DGD value as well as in fiber cutting process and these errors were compensated by slightly increasing RF frequency to 30.48GHz. In addition, a tunable delay line was used after PMF_2 in order to compensate δ, the phase shift due to length difference between two PMF pieces, which was about 23°.



(a)

(b)

Fig. 2. Measured relative phase in the case of (a) PMF_1(11.7m) and (b) PMF_2(35.1m) at the frequency of 30.48GHz. (-○- : V=3.9V, -●- : V=7.8V)

Fig. 2 (a) and (b) show the measured RF phases in the case of PMF_1 (L) and PMF_2 ($3L$) at 30.48GHz. The data were obtained by changing the incident polarization state with a polarization controller. In the figures, hollow circles represent the case with the modulator bias at $3.9V$ and solid ones at $7.8V$. As can be seen, the full range of 2π phase shift is successfully achieved.

Fig. 3 shows measured and calculated (using Eq. (3)) RF powers at different amounts of phase shifts. The maximum power variation is about 3dB as expected. If desired, this power variation can be reduced by adjusting the input power level according to the desired phase shift.

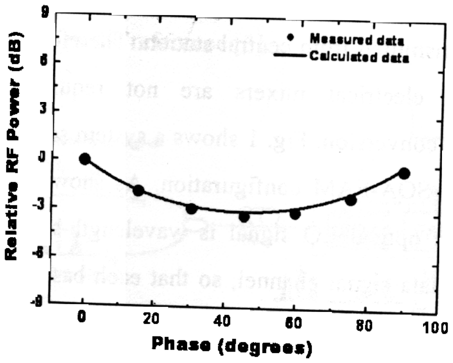


Fig. 3. Measured (-●-) and calculated (—) power variation as a function of phase change in PMF_1 with modulator bias condition of $3.9V$.

Ⅳ. Conclusion

A new photonic phase shifter based on the vector-sum technique is proposed and demonstrated using two pieces of PMF at the millimeter-wave frequency. The phase change can be controlled by changing the polarization state of light signal injected into PMF and the modulator bias voltage. Full phase shift up to 2π at 30.48GHz is successfully demonstrated.

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