Photonic phase shifters based on a vector-sum technique with polarization-maintaining fibers

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We propose and demonstrate a photonic phase shifter based a on vector-sum technique that uses polarization-maintaining fibers (PMFs). We achieved a continuous and full phase shift up to 2π at 30.48 GHz by controlling the polarization state of the light injected into two pieces of PMF of different lengths and applying two different modulator bias voltages.

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Phased array antennas that can greatly improve the performance of mobile communication systems have been studied extensively.[1] In particular, optically controlled phased array antennas are attractive because they provide many advantages such as lower loss, lighter weight, broader bandwidth, and greater flexibility than electrically controlled systems.[2] One of the key components in an optically controlled phased array antenna is a photonic phase shifter that can control rf phase easily and accurately in an optical manner.

Several designs for photonic phase shifters have been demonstrated based on a heterodyne mixing[3–5] or a vector-sum[2,6] technique. In the heterodyne mixing technique, two optical modes separated by the desired rf are generated by an optical frequency shifter, and the optical phase of one mode is changed by a $LiNbO_3$ modulator[3] or polymer modulators.[4,5] These signals are then combined and detected by a photodetector. With this method the change in optical phase results in a phase shift in the rf domain.

In the vector-sum technique, two sinusoidal signals that have the same frequency but different amplitudes and phases are summed. We can control the phase of the resultant signal by changing the amplitudes of two signals. In previously reported photonic vector-sum phase shifters, several modulators[2] or variable attenuators and optical delay lines[6] are required; thus the shifters are of limited practicality. In this Letter we propose and demonstrate a new photonic phase shifter based on a vector-sum technique that uses polarization-maintaining fibers (PMFs).

Two sinusoidal signals that have the same angular frequency (ω) but different amplitudes (A_1 and A_2) and phase difference ($\Delta\varphi$) can be summed into one sinusoidal signal:

$$A_1 \sin(\omega t) + A_2 \sin(\omega t + \Delta\varphi) = A \sin(\omega t + \varphi), \quad (1)$$

where

$$A = [A_1{}^2 + A_2{}^2 + 2A_1A_2 \cos(\Delta\varphi)]^{1/2}, \quad (2)$$

$$\varphi = \tan^{-1}\left[\frac{\sin(\Delta\varphi)}{A_1/A_2 + \cos(\Delta\varphi)}\right]. \quad (3)$$

As can be seen from Eq. (3), one can easily control the phase of the resultant signal by changing the amplitude ratio (A_1/A_2) of the two input signals at fixed $\Delta\varphi$.

Figure 1 shows a new configuration with which this scheme can be implemented in the optical domain. As shown in the figure, the laser output signal

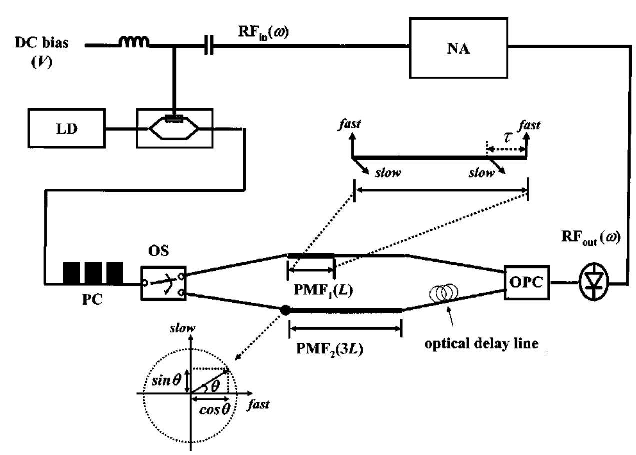

Fig. 1. Configuration and measurement setup for our photonic phase shifter: PC, polarization controller; OS, optical switch; OPC, optical power combiner; NA, network analyzer; LD, laser diode.

is intensity modulated by an electro-optic modulator and fed into either the upper or the lower PMF selected by an optical switch. The output optical intensity of the modulator is given by

$$\frac{I}{2}\left(1-\cos\left\{\frac{\pi}{V_\pi}[V_m\sin(\omega t)+V]\right\}\right), \tag{4}$$

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 for producing a π phase shift in the modulator output, and I is the optical intensity into the modulator.

The power of the modulated signal inside each PMF is transferred to two orthogonal polarization modes, fast and slow, with the coupling ratio determined by the incident polarization state controlled by a polarization controller. If the angle between the fast axis and the input polarization is θ ($0° \leqslant \theta \leqslant 90°$), the power coupled to the fast and the slow modes is proportional to $\cos^2\theta$ and $\sin^2\theta$, respectively.

The two modes in the PMF propagate with different propagation velocities, causing a difference in arrival time τ at the end of the PMF that is due to the PMF's differential group delay (DGD). The photocurrent (I_c) produced at the photodetector that has the modulation frequency component is given as

$$I_C \propto J_1\left(\frac{\pi V_m}{V_\pi}\right) I \sin\left(\frac{\pi V}{V_\pi}\right)[\cos^2(\theta)\sin(\omega t) + \sin^2(\theta)\sin(\omega t+\omega\tau)] = A\sin(\omega t+\varphi), \tag{5}$$

where

$$A = J_1\left(\frac{\pi V_m}{V_\pi}\right) I \sin\left(\frac{\pi V}{V_\pi}\right)\left\{1+\frac{1}{2}\sin^2 2\theta \times[\cos(\omega\tau)-1]\right\}^{1/2}, \tag{6}$$

$$\varphi = \tan^{-1}\left[\frac{\sin^2\theta\sin(\omega\tau)}{\cos^2\theta+\sin^2\theta\cos(\omega\tau)}\right]. \tag{7}$$

In relation (5) it is assumed that φ, the phase of the detected signal, is zero when θ is zero or that all the incident power is coupled into the fast mode. As can be seen from Eq. (7), changing θ from 0 to $\pi/2$ tunes φ from 0 to $\omega\tau$ when $\omega\tau<\pi$ or from π to $\omega\tau-\pi$ when $\omega\tau>\pi$. If we set the value of $\omega\tau$ to $\pi/2+2k\pi$ (k an integer) by fixing length L of a PMF (PMF_1) at a given rf, φ can be tuned from 0 to $\pi/2$. If the value of $\omega\tau$ is set to $3\pi/2+2k\pi$ (k an integer) by use of another piece of PMF with length $3L$ (PMF_2), Eq. (6) tells us that φ can be tuned from π to $\pi/2$. However, this turning range ignores the additional phase shift that is due to the difference in length between the two pieces of PMF. To explain this additional phase shift we modify relation (5) for PMF_2 as follows:

$$I_C \propto J_1\left(\frac{\pi V_m}{V_\pi}\right) I \sin\left(\frac{\pi V}{V_\pi}\right)[\cos^2(\theta)\sin(\omega t+\delta) + \sin^2(\theta)\sin(\omega t+\omega\tau+\delta)] = A\sin(\omega t+\delta+\varphi), \tag{8}$$

where δ is introduced to account for the phase shift that is due to the difference in length between PMF_1 and PMF_2 and δ is given as $\delta=\omega(3L-L)n/c$, where c is the velocity of light and n is the refractive index of the fast mode because our reference is taken with respect to the fast mode. The φ tuning range is then $\pi+\delta$ to $\pi/2+\delta$. Consequently the range from $\pi/2$ to $\pi/2+\delta$ cannot be covered by use of two pieces of PMF. To solve this problem we insert a fixed delay line that makes $\delta=2v\pi$ (v an integer) after PMF_2. With this configuration, a change of θ from 0 to $\pi/2$ can produce a rf phase shift from 0 to π with two pieces of PMF.

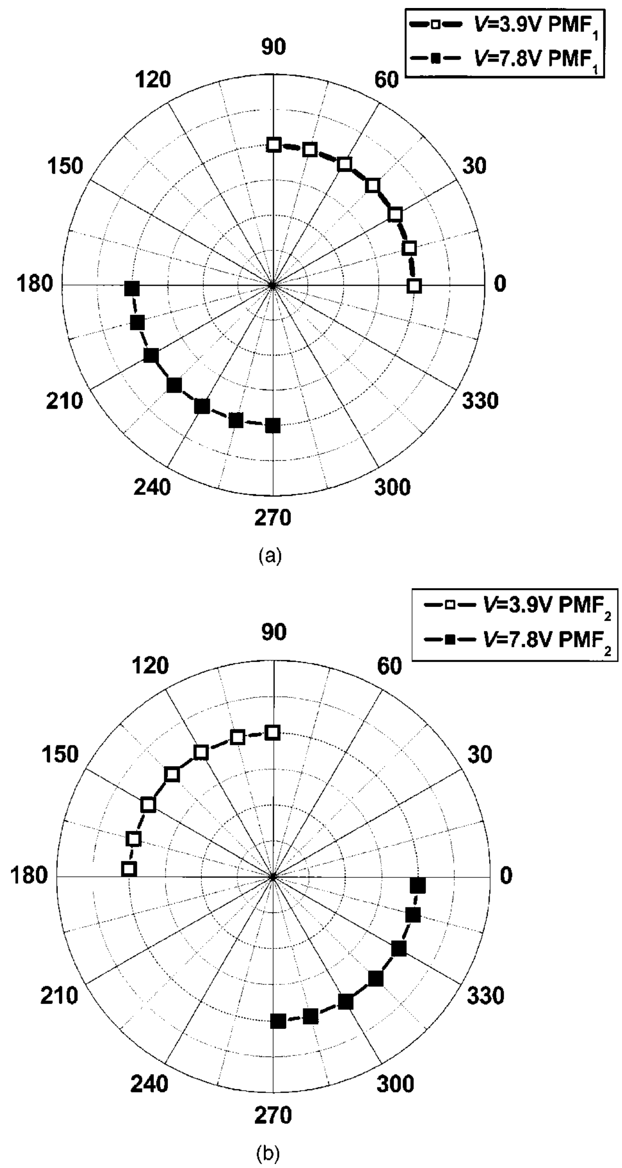

Fig. 2. Measured relative phase for (a) PMF_1 (11.7m) and (b) PMF_2 (35.1m) at a frequency of 30.48 GHz.

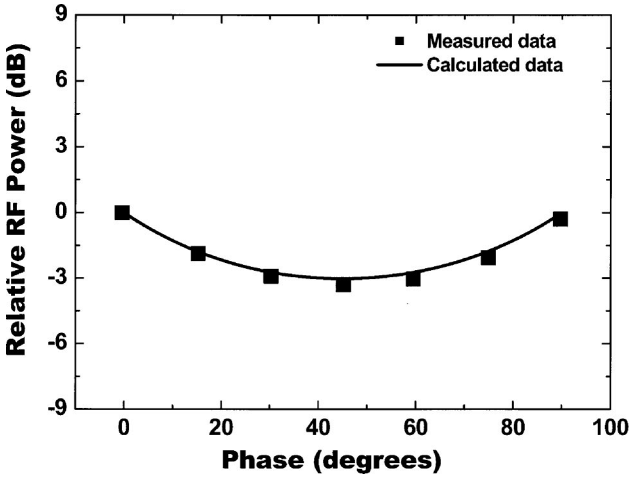

Fig. 3. Measured and calculated variation in power as a function of phase change in PMF_1 with a modulator bias condition of 3.9 V.

We can easily achieve the rf phase shift from π to 2π by changing the modulator bias voltage by an amount V_π because this produces a reversal of the sign of the detected rf signal.[7] In short, by controlling the polarization state of input light into two pieces of PMF that have the required lengths and by using two modulator bias voltages separated by V_π, we can achieve the full range of the phase shift from 0 to 2π.

With the experimental setup shown in Fig. 1 we measured rf phases of photodetected signals by using a network analyzer (HP8719ES) as the polarization state of the light injected into the two separate pieces of PMF was varied. In this system there is no optical coherence problem related to a source linewidth, because two orthogonal polarization modes are used.[8] The DGD value of commercially available PMF was experimentally measured from the first dip position in the PMF frequency response[9] and found to be $0.70\ \mathrm{ps}/m$. At 30 GHz the required PMF length L is $11.7\ m$ when $m=0$, and two pieces of PMF with lengths L and $3L$ with standard fiber connectors were made. There were, however, errors caused by uncertainties in the estimated DGD value as well as in the fiber cutting process, and we compensated for these errors by slightly increasing the rf to 30.48 GHz. In addition, a tunable delay line was used after PMF_2 to compensate for δ, the phase shift that was due to a difference in length between two of the PMF pieces, which was $\sim 23°$.

Figure 2 shows the measured rf phases for PMF_1 (L) and PMF_2 ($3L$) at 30.48 GHz. We obtained the data by changing the incident polarization state by using a polarization controller. In the figure, open squares represent the modulator bias at 3.9 V; filled squares, at 7.8 V. As can be seen, the full range of the 2π phase shift is successfully achieved.

Figure 3 shows measured and calculated [with Eq. (6)] rf powers at different amounts of phase shift. The maximum power variation is ~ 3 dB, but one can reduce this power variation by adjusting the input power level according to the desired phase shift.

Although the present measurement was made for a fixed rf of 30.48 GHz it is possible to tune the target rf to the PMF temperature. Using a $\mathrm{d}\tau/\mathrm{d}T$ value of $0.8 \times 10^{-3}\ (\mathrm{ps}/°\mathrm{C})/m$,[8] we can achieve a tuning range of ~ 3.36 GHz when $L=11.7m$ ($k=0$) and $\Delta T = 100\ °\mathrm{C}$. However, we can greatly extend this range by increasing the value of k. For example, when $k=1$ ($L=58.5m$), the tuning range is extended to 16.8 GHz, which is enough to cover the entire Ka band. Another possibility for tuning the rf is to use a photonic crystal fiber whose DGD can be tuned to the source wavelength.[10]

In summary, we have demonstrated a new photonic phase shifter based on the vector-sum technique and using two pieces of PMF. We control the phase change by changing the state of polarization of the light injected into the PMF and the modulator bias voltage. A full phase shift up to 2π at 30.48 GHz was successfully demonstrated. Although our demonstration was made at a single frequency, our scheme has no limitation in frequency as long as the required PMF length can be obtained. This scheme should be particularly useful for applications at frequencies beyond 40 GHz at which electronic phase shifters are not readily available.

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