Integrated Polymer Photonic RF Phase Shifters for Optically Controlled Beam Forming Systems

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Abstract — **We have demonstrated integrated polymer photonic RF phase shifter arrays with a novel balanced design, new symmetric mode configurations and a simplified fabrication procedure, which is capable of removing conventional drawbacks in this type of phase shifter architecture. These devices showed four independent highly linear RF phase outputs and negligible RF power fluctuation at the modulation frequency of 20 GHz.**

I. INTRODUCTION

Photonic-based beam forming systems provide many advantages compared with those employing only microwave signal processing. Various types of photonic-based beam forming techniques have been demonstrated [1]-[6]. One of the most flexible and simplest approaches is using phase control based on optoelectronic integrated circuits (OEIC) technology [5], [6]. In such systems, the photonic radio frequency (RF) phase shifters are the key elements. They can control multiple RF phases using DC voltages and feed the independent phase outputs into the antenna array to perform rapid and continuous beam forming functions.

Most importantly, it is essential to integrate a phase shifter array providing multiple independent phase outputs in a single chip. This reduces the complexity of RF feed structures and needs only a single RF and optical source.

In this paper we describe the performance of a four-element photonic RF phase shifter array with an advanced configuration. We anticipate it will extend the range of applications for these devices with simpler fabrication procedures.

II. THEORY

The architectures described in [5], [6] exhibit a lack of phase linearity and substantial amount of RF power variation as the RF phase is tuned over 2π. These effects are caused by the presence of the main lobe from the single-sideband (SSB) modulator unit, which is mathematically represented by $J_0(\Delta)$. The optical signal from the control arm will be added to this main lobe and then mixed with the side lobe at the photodiode resulting in degradation of RF phase and power characteristics.

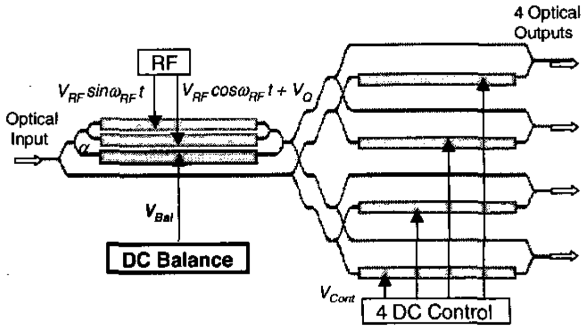

Fig. 1. The schematic diagram for the four-element RF phase shifter array with the balanced design

Having recognized the origin of the detrimental effects, we have developed a simple solution. Fig. 1 represents the schematic diagram for our four-element RF phase shifter array. It consists of a SSB modulator incorporating a balancing arm and four independently controlled optical phase shifters. The balancing arm is intended to cancel out the unwanted main lobe from the SSB modulator by providing a signal with opposite phase and equal magnitude. The modulated optical output from the balanced SSB modulator is split into four branches and combined with the four outputs from the optical phase shifters. At the photodiodes, the mixing of these signals gives rise to the independent RF phase output. This signal distribution in a planar geometry can be achieved through the use of low crosstalk waveguide crossings and S-bend waveguide structures. The performance of these devices could be severely impacted by that of the optical waveguide crossings and as such they need to be carefully implemented.

The output intensity at the modulation frequency ω_{RF} for each output port is given by

$$I_{\omega_{RF}}(t) = \frac{1}{4(1+\alpha)^2} A_{RF} J_1(\Delta)\cos(\omega_{RF}t + \varphi_{RF}) \qquad (1)$$

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where

$$A_{RF} = \left\{ \left[J_0(\Delta) + 2\alpha \cos\phi_{Bal} + 2(1+\alpha)\cos\phi_{Cont} \right]^2 + \left[J_0(\Delta) + 2\alpha \sin\phi_{Bal} + 2(1+\alpha)\sin\phi_{Cont} \right]^2 \right\}^{1/2} \quad (2)$$

$$\varphi_{RF} = \tan^{-1}\left[\frac{J_0(\Delta) + 2\alpha \sin\phi_{Bal} + 2(1+\alpha)\sin\phi_{Cont}}{J_0(\Delta) + 2\alpha \cos\phi_{Bal} + 2(1+\alpha)\cos\phi_{Cont}} \right] \quad (3)$$

Here V_π is the half-wave voltage, $\Delta = \pi \cdot V_{RF}/V_\pi$ is the modulation depth, $\phi_{Cont} = \pi \cdot V_{Cont}/V_\pi$ is the optical phase shift by the control DC bias, $\phi_{Bal} = \pi \cdot V_{Bal}/V_\pi$ is the optical phase shift by the balancing DC bias and α is the splitting ratio at the balancing arm. The desired phase and magnitude of the optical signal for the balancing arm can be established by the balancing DC bias and the splitting ratio, respectively.

Fig. 2 and Fig. 3 shows the calculated RF phase and power characteristics of the balanced structure as a function of control voltage for a modulation depth of 0.5. For the choice of $\alpha = J_0(\Delta)/\sqrt{2}$ with $\phi_{Bal} = 5\pi/4$, the undesirable terms, $J_0(\Delta)$, completely disappear and the ideal characteristics for the RF phase and power can be obtained such that

$$A_{RF}^2 = const., \quad \varphi_{RF} = \tan^{-1}\left[\frac{2\sin\phi_{Cont}}{2\cos\phi_{Cont}} \right] = \phi_{Cont} \quad (4)$$

This indicates that the RF power does not vary at all and the RF phase shift is perfectly linear with respect to the control DC voltage, which makes these devices highly suitable for the optically controlled phase array antenna systems.

Assuming a simple symmetric splitting at the balancing arm, i.e. $\alpha = 1$, with $\phi_{Bal} = 5\pi/4$, the system also shows a highly linear phase characteristic and substantial reduction of power fluctuation compared with the structure without balancing arm. In this case, the unwanted signal can be only partially canceled out since the balancing power becomes unequal to the main lobe from the SSB modulator unit. Nevertheless, this significant improvement of nearly one order of magnitude is capable of removing one of the strongest objections to this type of phase shifter architecture.

II. Device Characterization

Fig. 4 shows the balanced multiple output photonic RF phase shifter fabricated in our novel polymer materials using advanced polymer modulator technologies [7], [8]. For the simplicity of the design, the splitting ratio of the balancing arm, α, was set to be 1. The single mode (SM) ridge optical waveguides were fabricated using the new inverted rib structures, which ultimately resulted in much simpler fabrication procedures and lower propagation losses. Also the SM waveguide structures were designed to provide the symmetric mode shape with a rib depth of 0.8 µm and waveguide width of 4 µm [8]. For the minimum device length and insertion loss, raised-sine S-bend waveguide structures have been used in all the optical waveguide bending sections [9]. The test structures for the S-bend and waveguide crossings were fabricated on the same wafer. The measured bending losses of the S-bend structures were less than 0.2 dB. The measured excess optical loss due to the crossing was less than 0.5 dB and the optical waveguide crossings exhibited a crosstalk level of less than –28 dB.

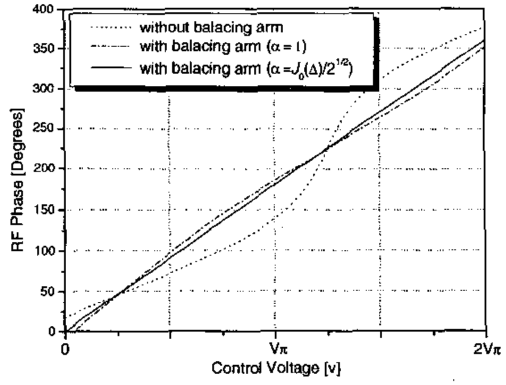

Fig. 2 The calculated RF phase characteristics of the balanced structure for a modulation depth of 0.5

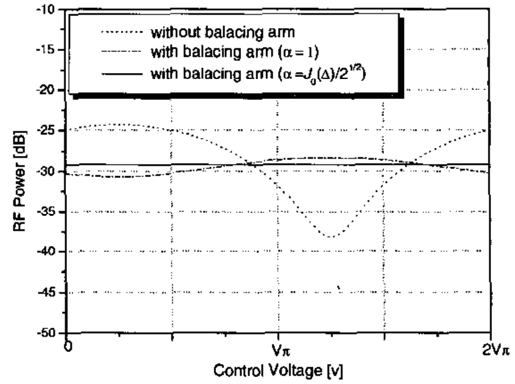

Fig. 3 The calculated RF power characteristics of the balanced structure for a modulation depth of 0.5

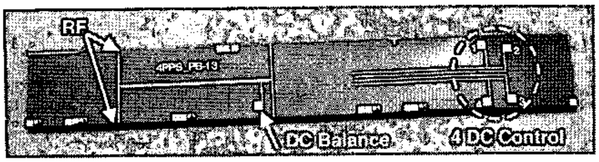

Fig. 4. The balanced multiple output photonic RF phase shifter fabricated in the APC-CPW polymer material

III. EXPERIMENTAL RESULTS

The experimental setup for the photonic RF phase shifter is similar to that described in [7]. An additional DC bias is applied to the balancing arm to provide the balancing phase of $5\pi/4$.

Fig. 5 and Fig. 6 show the measured RF phase and power of a single element as a function of time at the modulation frequency of 20 GHz and the modulation depth of 0.58. The linear relationship between voltage and time in the control triangular waveform enabled a one-to-one mapping between the measured RF phase (or power) and the control DC voltages. For the control triangular waveforms of $2V_\pi$ ($-V_\pi \sim V_\pi$), the RF phase was fully tuned by 360° with a high level of linearity and the RF power varied by less than 4 dB as expected from (2) and (3). Note that a single control of 360 ° of the RF phase shift corresponds to the half cycle of the voltage change in triangular waveforms in time domain (25 ms). Accordingly, Fig. 5 and Fig. 6 represent 8 times full operation within 200 ms. This performance can be even further improved by employing the design with the optional splitting ratio of the balancing arm as described before.

These RF phase shifters should contain the most important feature that the RF phases of an array element are independently controlled. In order to confirm this, four triangular waveforms of $2V_\pi$, set by the equal time delays, were applied to the four DC control arms. The measured RF phase characteristics are shown in Fig. 7. Almost identical characteristics having the phase shift of 360° were observed for all output ports. It can be also seen from Fig. 7 that, at a given time frame, this arrangement results in the same effect generated by four different voltages and consequently introduces the independent phase shifts at four output ports. In addition, the independent control of the RF phase was also demonstrated by applying the triangular waveforms having different peak-to-peak voltages to each control arm (Fig. 8).

The new generation of phase shifter is currently being

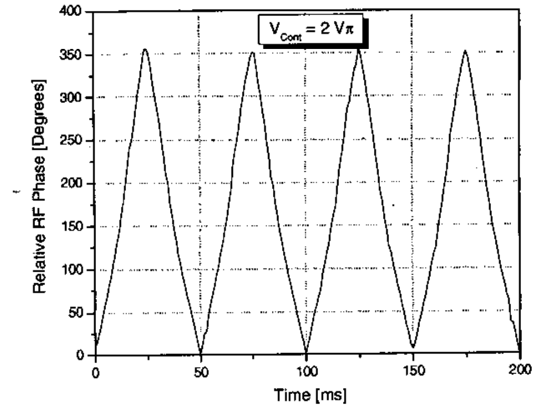

Fig. 5. The measured RF phase as a function of time

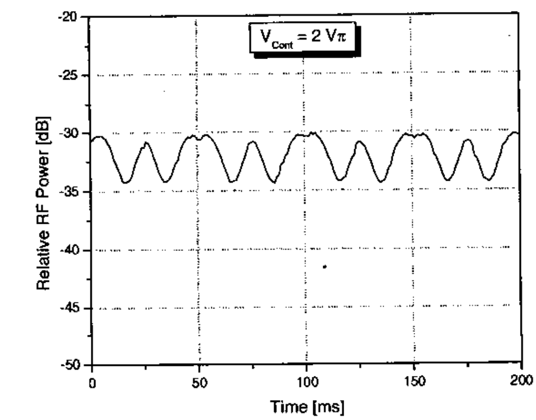

Fig. 6. The measured RF power as a function of time

developed, which can even reduce the complexity from applying additional DC biases. Instead of using normal Y-junction splitting structures, asymmetrical 1-by-2 multimode interference (MMI) couplers can be used in front of the SSB modulator and the balancing arm as shown in Fig. 9. This eventually will offer the built-in biases for the required optical phase shifts removing the need for the DC biases of V_Q and V_{Bal}. The test devices of these MMI couplers were fabricated and measured. They showed the good ability to provide the desired phases at two output ports. Therefore, these MMI integrated photonic RF phase shifters are expected to allow the simpler operation only requiring a RF feeding and control DC biases.

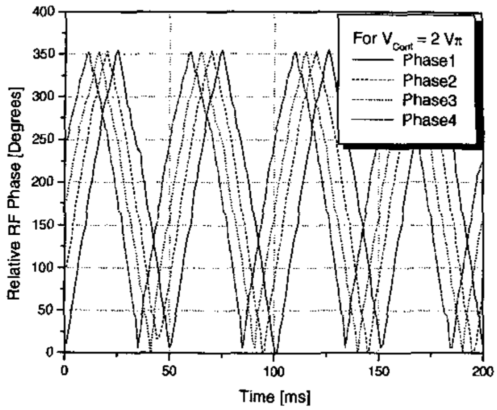

Fig. 7. The independently controlled four phase outputs introduced by equal delays on the triangular control voltages

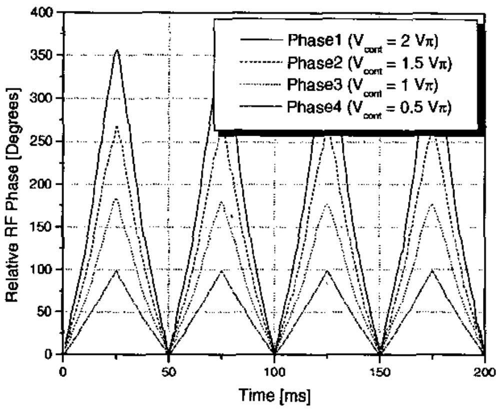

Fig. 8. The independently controlled four phase outputs introduced by the different triangular control voltages

IV. Conclusion

We have demonstrated a polymer-based four-element photonic RF phase shifter array in a single chip. By employing a novel design to remove the conventional drawbacks of this type of device, four phase outputs can be independently controlled with high linearity and negligible power fluctuation. A simple vertical stack of these devices will form an N × N photonic RF phase shifter array without increasing complexity and will contribute to the future photonic phased array systems.

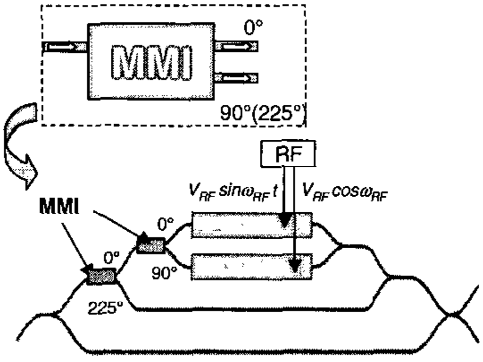

Fig. 9. The realization of the new generation of phase shifter structure incorporating MMI couplers

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