# Multiple Output Photonic RF Phase Shifters For Optically Controlled Radar Systems

Harold Fetterman[1], Jeehoon Han[1], Hua Zhang[2], Hernan Erlig[2], Dan Chang[1], Min-Cheol Oh[2] and William Steier[3]

1. Electrical Engineering Department, University of California Los Angeles, Los Angeles, CA 90095
2. Pacific Wave Communications, Los Angeles, CA 90024
3. Electrical Engineering Department, University of Southern California, Los Angeles, CA 90089

*Abstract* — **Photonic RF phase shifters with independent multiple outputs have been fabricated using our novel polymer modulator technology. These integrated planar devices incorporated low crosstalk optical waveguide crossings, which were critical to the independent operation of RF phase outputs. The measured RF phase shift characteristics at 20 GHz were approximately linear up to ~150° with respect to DC control voltages. Also new systems, currently being developed, will provide more linear transfer function for RF phase and relatively constant amplitude with four outputs. Compact optically controlled antenna systems, based on this technology, will be presented.**

## I. INTRODUCTION

The implementation of phased array systems for radar and advanced space communication applications is hindered by the need for complex RF feed structures and a large number of active phase-shifting elements. Photonic approaches for beam forming applications have been identified as suitable replacements because they have many attractive features compared with those employing just microwave signal-processing [1]-[5]. Photonic RF Phase Shifters are critical elements in such systems.

In earlier work, we successfully demonstrated a single element photonic RF phase shifter fabricated from the polymer material, CLD2/ISX [6]. As an expansion of this idea, we now present the design, fabrication, and performance of multiple output photonic RF phase shifters in a single chip operated at 20 GHz. This multiple output configuration, in a planar form, was enabled by the use of low crosstalk S-bend optical waveguide crossings. Also, we discuss our new power balanced photonic RF phase shifters, which can substantially mitigate the RF power variation and provide more linear transfer function for RF phase. These devices have been fabricated from a new EO polymer material, CPW1/APC and employ our state-of-the-art polymer modulator technology [7].

## II. OPERATING PRINCIPLE

### *A. Multiple output photonic RF phase shifters*

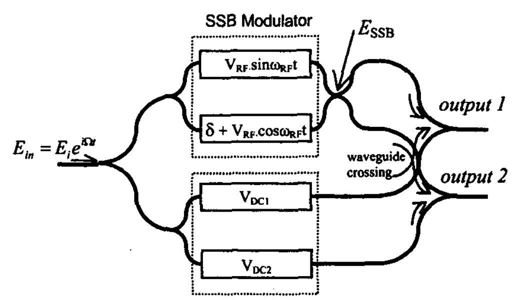


Fig. 1. Device architecture for the photonic RF phase shifter with two independent outputs.

Fig. 1 shows the device architecture for the photonic RF phase shifter with two independent outputs. It consists of a single-sideband (SSB) modulator embedded in one arm of a Mach-Zehnder (MZ) and two independently controlled optical phase shifters on the other arm.

The SSB modulator is driven at a frequency $\omega_{RF}$ with RF signals having equal amplitudes, $V_{RF}$ but 90° out-of-phase and additional DC bias is applied to one arm at the SSB modulator for the optical phase shift, $\delta$. The mixing of the each output from the SSB modulator with the output from the individual optical phase shifter gives rise to the independent RF phase output. It can be seen that RF phases at both output channels are controlled by changes in control DC biases from two optical phase shifters [6]. This signal distribution in a planar geometry is achieved through the use of low crosstalk S-bend waveguide crossings.

Also only when the bias conditions described above for SSB modulator are fully satisfied, can the RF phase shifter operate properly. It can be seen that when $\delta = \pm\pi/2$, there is only one sideband at $\Omega - \omega_{RF}$ or $\Omega + \omega_{RF}$ and it guarantees proper operation of RF phase shifter [8]. Under any other bias conditions there are

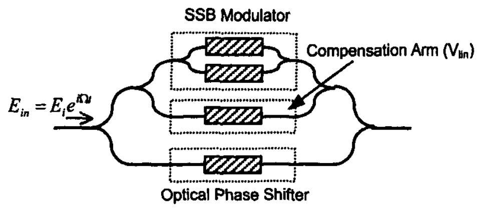


Fig. 2. Device architecture for the power balanced photonic RF phase shifter with an additional MZ.

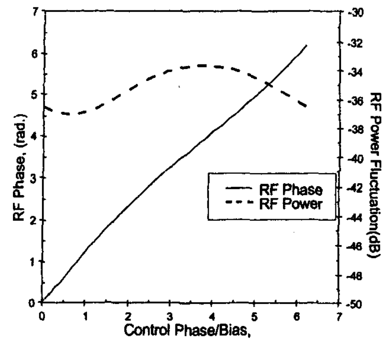


Fig. 3. Calculated RF phase and power for the power balanced structure as a function of the control phase.

double sidebands at both frequencies. This type of SSB modulators can also be used to optically distribute microwaves and millimeter signals while mitigating the deleterious effects of fiber dispersion [8,9].

*B. Power Balanced Photonic RF Phase shifters*

From [6] for $\Delta = 2.7$ the RF phase is linearly dependent on the control voltage; however, to achieve this condition requires a considerable amount of RF drive power. As $\Delta$ is reduced below 2.7, which is within the range of our experimental value, the linear dependence of the RF phase on control voltage disappears and it is replaced by a strong non-linear dependence. In addition, the generated RF power shows excessive variation of RF power as RF phase is tuned. These effects are inherent to the phase shifter architecture illustrated in Fig. 1. and arise from the mixing between the arms of the SSB modulator unit. This degrades phase shifter performance and is undesirable for the intended application, namely photonic control of phased arrays.

In order to eliminate this problem the power balanced structure shown at Fig. 2. was introduced [10]. It incorporates an additional MZ in which the linearizing

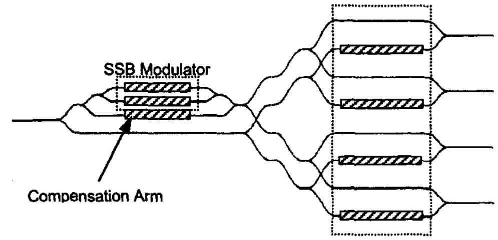


Fig. 4. Device architecture for the 1-by-4 power balanced photonic RF phase shifter for 4-element phased array system.

bias, $V_{lin}$, (or phase, $\gamma$,) is chosen to minimize the impact of the undesirable mixing term. Under ideal operating conditions this new structure, as the RF phase is tuned, is capable of maintaining the RF power fluctuation below 4 dB and providing much greater linearity of RF phase transfer function (Fig. 3.).

The integrated module shown at Fig. 4. is currently being developed, which incorporates the advantages of our power balanced structure in conjunction with four independent outputs in a parallel configuration.

## III. DEVICE FABRICATION

The devices were fabricated using our polymer modulator technology. A Cr/Au layer covered the Si wafer and acted as the ground plane for the microstrip lines, which drove the SSB unit. The polymer stack consisted of three layers: a lower cladding spun from UV-15, a core layer spun from our CPW1/APC material system, and an upper cladding spun from UFC170. This core material exhibits high EO coefficient and low material loss at 1.3 and 1.55 μm [6]. Ridged optical waveguides were defined via RIE etching where the ridge height was set to 0.4 μm with a 3.0 μm thick core. Ridge width for these devices was 8 μm, which ensured single mode operation. Raised sine S-bends were used in all the optical waveguide bending sections of the device [11]. This allowed a dramatic reduction in device length compared to traditional Y-branches. In addition, the optical waveguide crossings exhibited crosstalk levels down 20 dB and an optical loss due to the crossing less than 1 dB. This low crosstalk level is crucial to ensure independent phase shifting outputs. Then, the microstrip lines were vertically aligned to the optical waveguides in the interaction regions and provided enhanced overlap integrals thereby reduced the required driving voltage. The SSB modulator with the interaction length of 1.5 cm exhibited a DC $V_\pi$ of 6.4 V.

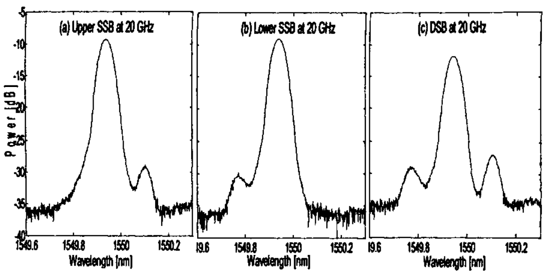


Fig. 4. Optical spectrums measured at the output of the SSB modulators driven by a 20 GHz source. (a) and (b) Spectrum at a DC bias, which yields either upper or lower SSB. (c) Spectrum at a DC bias, which yields double side bands.

## IV. PHASE SHIFTER CHARACTERIZATION

The individual phase shifter outputs were characterized using an experimental set-up similar to that described in [6]. However, in this case the phase shifters were illuminated by a 1.55 μm source and an 8720ES analyzer was used. Port 1 of the 8720ES drove the shifters at 20 GHz through a balanced hybrid splitter that ensured quadrature components of equal amplitudes. A function generator was used to control the RF phase outputs and triggered the network analyzer in order to synchronize the data gathering. A 50 Hz triangular waveform acted as the control voltage $V_{DC1,2}$. The linear relationship between voltage and time for the triangular waveform allowed an one-to-one mapping between the measured RF phase and power and the applied voltage $V_{DC1,2}$.

The proper operation of the SSB unit at 20 GHz was confirmed first with test SSB modulators fabricated on the same wafer. The measurement results for different biases are shown in Fig 4. Again, this bias condition corresponded to the required bias for proper operation of the RF phase shifter. For all other biases double sidebands were observed as expected.

Fig. 5 (a) and (b) show the measured RF phases and relative powers for the independent phase shifter outputs. Fig. 5 (a) shows the measured RF phases as a function of control voltages. For triangular waveforms of 6.4 $V_{pp}$ (-3.2 V ~ 3.2 V), the RF phases were observed to change by about 150° at both outputs. Again, the identical phase shifts at both outputs were achieved through the use of low crosstalk S-bend waveguide crossings. Over a significant portion of this range the transfer characteristic was fairly linear. Fig. 5 (b) shows the measured RF relative powers. The RF power fluctuated by nearly 13 dB at both outputs as the RF phases were tuned.

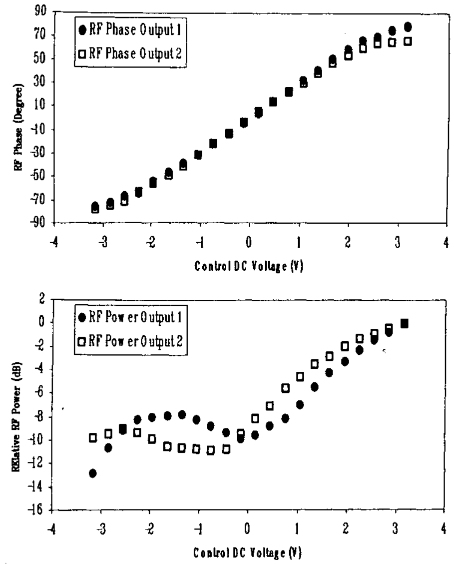


Fig. 5. (a) Measured RF phase for the two independent phase shifter outputs. (b) Measured relative RF power for the two independent outputs. The measurements were made as a function of control voltage.

## V. CONCLUSION

As one of the critical components in photonic microwave signal-processing systems, we have demonstrated integrated polymer-based photonic RF phase shifters with two independent outputs in a single chip. At 20 GHz, a linear transfer function between RF phase and control bias has been achieved over a 150° range. The characteristic RF power fluctuation was also observed. However, a solution to this problem has already been implemented as discussed. A new design with four independent outputs is in the process of being developed, in which less RF power variation is obtainable by minimizing the unwanted mixing terms arising in the SSB modulator. This improved architecture with multiple outputs will significantly contribute to future photonic phased array systems.

## ACKNOWLEDGEMENT

This work was supported in part by Air Force Office of Scientific Research (AFOSR).

## REFERENCES


[1] Coward J.F., Yee T.K., Chalfant C.H., and Chang P.H., "A photonic integrated-optic RF phase shifter for phased array antenna beam-forming applications", *Journal of Lightwave Technology,* vol. 11, no. 12, pp. 2201-2205, Dec 1993.

[2] Tamburrini M., Parent M., Goldberg L., and Stillwell D.; "Optical feed for a phased array microwave antenna", *Electronics Letters*, vol. 23, no. 13, pp. 680-681, Jun 1987.

[3] Kamiya Y., Chujo W., Koji Y., Matsumoto K., Izutsu M.,and Sueta T., "Fiber Optic Array antenna using optical waveguide structures", *IEEE International Symposium Digest, Antennas and Propagation,* vol. 2072, pp. 774-777, May 1990.

[4] Jez D.R., Cearns K.J., and Jessop P.E., "Optical waveguide components for beam forming in phased array antennas", *Microwave and Optical Technology Letters,* vol. 15, no. 1, pp. 46-49, May 1997.

[5] S. R. Henion and P. A. Schulz, "Electro-optic phase array transmitter", *IEEE Photonic Tech. Lett.*, vol 10, March 1998, p424-6

[6] S. Lee, A. Udupa, H. Erlig, H. Zhang, Y. Chang, C. Zhang, D. Chang, D. Bhattacharya, B. Tsap, W. Steier, L. Dalton, and [1]H. Fetterman, "Demonstration of a Photonically Controlled RF Phase Shifter," *IEEE Microwave and Guided Wave Lett.*, vol. 9, no. 9, 1999, pp. 357-9.

[7] M. Oh, H. Zhang, A. Szep, V. Chuyanov, W. Steier, C. Zhang, L. Dalton, H. Erlig, B. Tsap, and H. Fetterman, "Electro-optic polymer modulators for 1.55 mm wavelength using phenyltetraene bridge chromophore in polycarbonate," *Appl. Phys. Lett.*, vol. 76, no. 24, 2000, pp. 3525-7.

[8] G. H. Smith, D. Novak and Z. Ahmed, "Technique for optical SSB generation to overcome dispersion penalties in fiber-radio system", Electronics Letters, vol 33, no1, 1997, pp.74-5.

[9] E. Vergnol, F. Devaux, D. Tanguy and E. Penard, "Integrated lightwave millimetric single sideband source: design and issues", J. Lightwave Technology, vol 16, no7, 1998, pp. 1276-84.

[10] H. Erlig, D. Chang, M. Oh, J. Han, Y. Chang, C. Zhang, B. Tsap, H. Fetterman, and W. Steier, "Applications of State-of-the-Art Polymer Modulators," *Optical Society of America Conference on Integrated Photonics Research*, paper ItuH3-1, Monterey, Ca, USA, June 2001, invited presentation.

[11] H. Nishihara, M, Harura, T. Shhara, "Optical Integrated Circuits" *McGraw-Hill*, 1989.