Wide-Band RF Photonic Second Order Vector Sum Phase-Shifter

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***Abstract*—A novel technique to extend the phasing range of the vector sum phase shifter by exploiting its second order response is proposed and implemented. A continuously variable phase shift is demonstrated between 8 and 16 GHz with phasing range exceeding 450° measured at 16 GHz. Good agreement between the predictions and measurements has been obtained.**

***Index Terms*—Microwave photonic, photonic beamforming, TTD.**

I. INTRODUCTION

ADVANCED electronic warfare requires antenna systems that are steerable and broad in instantaneous bandwidth. Phased array antenna (PAA) technologies have been identified as a principal solution to meet these requirements [1]. A major component of a PAA is the beam-forming network (BFN). For broad instantaneous bandwidth, time shifting or true time delay (TTD) BFNs are often utilized.

A broadband BFN consists of many TTD phase shifters that independently feed the antenna array. Many TTD phase shifters have been proposed over the years. These include switched delay line [2], dispersive fiber prism [3] and fiber grating devices [4]. Though promising, these phase shifters are complex and usually expensive to implement. Alternatively, Rotman lenses [5] are also used. Although Rotman lens solutions are practical, they could become very bulky and inflexible.

We have previously demonstrated a novel broadband vector sum phase shifter (VSPS) [6]. It was found that the VSPS exhibited an excellent phase linearity, but the phase shifting range was limited to 120°. This phasing range was not sufficient on its own even for being used in a modest four element PAA [7]. Extending the VSPS phasing range was therefore necessary.

In this letter, we propose and demonstrate a novel technique to extend the phase shifting range of the VSPS by exploiting its second order response. The proposed phase shifter is thus named Second Order Vector Sum Phase Shifter (SO-VSPS). The SO-VSPS has a sufficient phasing range for steering a four element PAA 30° off broadside [7].

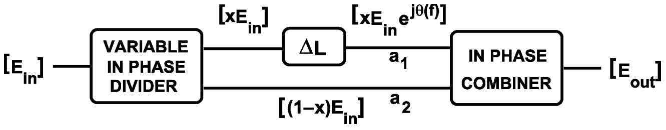

Fig. 1. Schematic diagram of the VSPS.

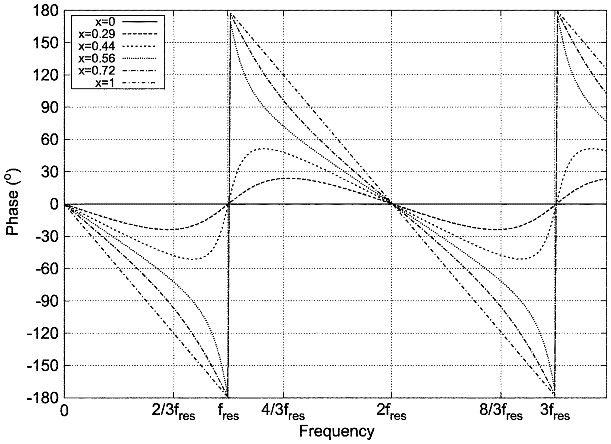

Fig. 2. VSPS phase transfer function for several selections of x value.

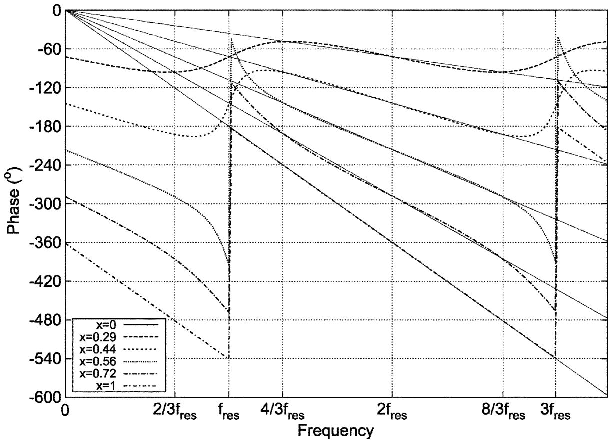

Fig. 3. Phase responses of Fig. 2 with offsets to mimic TTD characteristics. The thin solid lines (all starting from zero) represent the ideal TTD phase characteristics.

II. PRINCIPLE OF OPERATION

Since the SO-VSPS is an extension of the VSPS, it is useful to re-visit the VSPS principle of operation. A schematic diagram of the VSPS is presented in Fig. 1. Its transfer function was derived in [6] and is given as $(1-x)+xe^{j\theta(f)}$, where $x:(1-x)$ is

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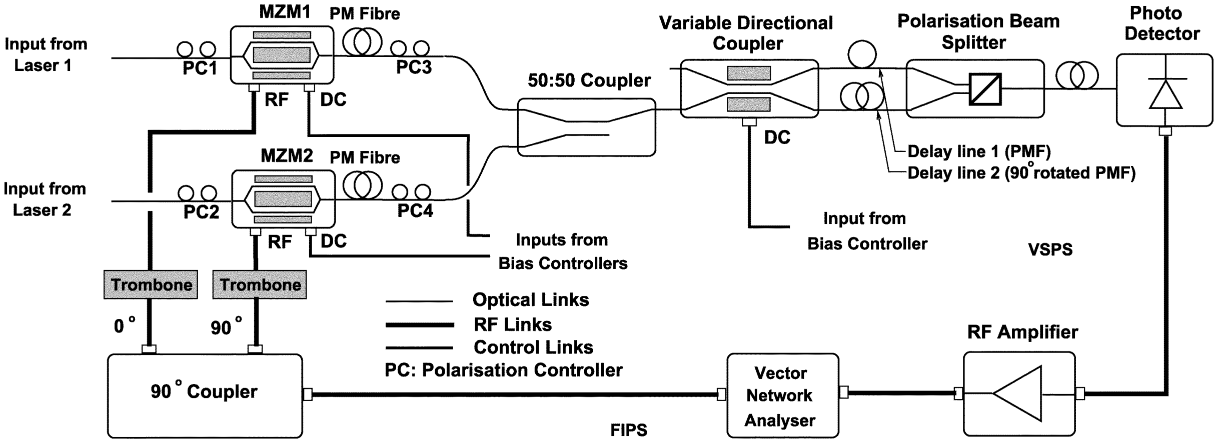

Fig. 4. Experimental configuration to demonstrate the SO-VSPS.

the power splitting ratio between the VSPS arms and $\theta(f)$ is the phase shift due to the delay line ΔL of Fig. 1.

Fig. 2 presents the VSPS phase transfer functions calculated at several x values. The phases are plotted over a wider range than the VSPS nominal operating frequency range to show the cyclically behaved characteristic of the device. The VSPS device resonates at frequencies where the signals in the two delay arms are out of phase, i.e., at frequencies $f_n = (n + (1/2))(1/\tau)$, where $n = 0, 1, 2, \ldots$ and τ is the time delay due to ΔL [6]. The lowest resonant frequency is called the fundamental resonance ($f_{\mathrm{res}} = f_1$) and other resonant frequencies are the odd multiples of f_{res}. It is evident that the device has response from dc to f_{res} being repeated from $2f_{\mathrm{res}}$ to $3f_{\mathrm{res}}$. The range from f_{res} to $2f_{\mathrm{res}}$ behaves as the inverse of that from dc to f_{res}.

It is also observed that the phase linearity and magnitude variation around $2f_{\mathrm{res}}$ are similar to those around dc. It is conceivable that the second order frequency range from f_{res} to $3f_{\mathrm{res}}$ could be utilized. However, the frequency dependence of the phase around the second order region is not TTD, since the phase does not pass through zero at dc. It is proposed that the second order response of the VSPS could be modified to mimic TTD characteristics over a limited band by adding a frequency independent phase offset as shown in Fig. 3. It is thus concluded from Fig. 3 that by using the phase offset, the phase shifting range could be extended from 0–120° to 0–480°.

The phase offset must be chosen such that the resulting response is a good fit to a line intersecting zero-phase at dc. A different phase offset is therefore required for each TTD setting. To realize the phase offset required for the SO-VSPS, it will be necessary to implement a Frequency Invariant Phase Shifter (FIPS) with arbitrarily selectable phase between 0° and 360°.

III. DEMONSTRATION OF SO-VSPS

Several vector modulation phase shifters that meet the FIPS requirements have been demonstrated [8]–[10]. Among them, it is found that the device reported in [10] is realized photonically, hence it is employed in this investigation. A schematic diagram of the SO-VSPS with the FIPS placed in front of the VSPS is presented in Fig. 4.

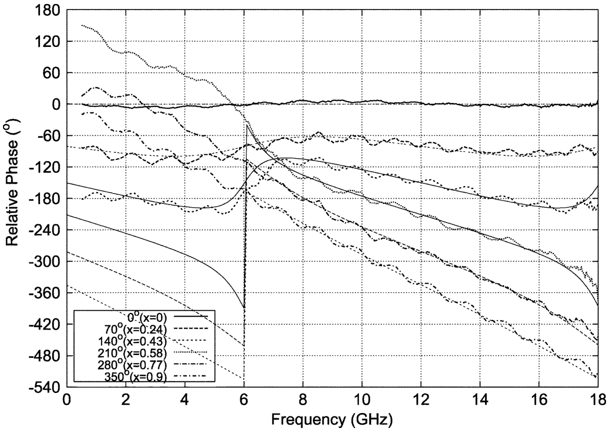

Fig. 5. Measured (thick lines) and predicted (thin lines) phase of the demonstrated SO-VSPS. Curves are labeled with phase quoted at 12 GHz and the value of the experimental parameter x in parentheses.

The FIPS is implemented using dual optical Mach Zehnder modulators (MZM's). These MZM's are driven by RF signals with an identical amplitude and 90° phase offset. The VSPS is produced with $f_{\mathrm{res}} = 6$ GHz. Orthogonally aligned polarization maintaining (PM) fiber delay lines and PM couplers are used to implement the VSPS to suppress coherent interference and to minimize polarization drift [11]. Alignment of polarization for the VSPS has been achieved through the utilization of polarization controllers PC 3 and PC 4.

A vector network analyzer is used to analyze the system response as shown in Fig. 4. The FIPS was set up and controlled as described in [10]. Using this control technique, the FIPS exhibits a constant amplitude response with an arbitrarily selectable phase between 0° and 360°. At the centre of the second order band (12 GHz), the VSPS always produces 0° phase shift. The SO-VSPS phase response is therefore totally determined by the FIPS. Using this property, setting of the SO-VSPS is performed by first adjusting the FIPS to provide the entire required phase shift at 12 GHz, then adjusting the VSPS to obtain the necessary phase slope.

The measured SO-VSPS phase and magnitude responses for several selected settings are presented in Figs. 5 and 6 respectively. It is evident from Fig. 5 that approximately TTD phase shift is exhibited between 8 and 16 GHz. The phasing range was measured to be 0–450° at 16 GHz. In Fig. 6, cancellation due to device resonance is evident at f_{res} and $3f_{\mathrm{res}}$ as expected. Ripple

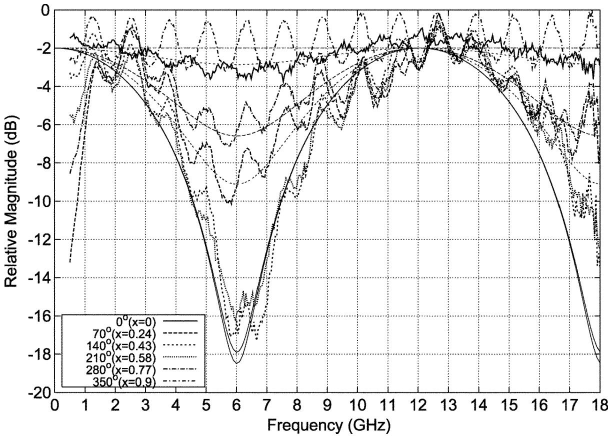

Fig. 6. Measured (thick lines) and predicted (thin lines) magnitude of the demonstrated SO-VSPS. Curves are labeled with phase quoted at 12 GHz and the value of the experimental parameter x in parentheses.

is also evident in both the amplitude and phase responses. Apart from this ripple, an excellent match between theory and measurement is achieved.

IV. DISCUSSION

The ripple observed in Figs. 5 and 6 could be attributed to the Fabry–Perot reflections from the index mismatched end facets of the VSPS variable directional coupler (VDC). This ripple is not intrinsic to the SO-VSPS device and could be eliminated by employing anti-reflection coatings before the VDC pigtailing. It was also observed that the phase shifting range at 16 GHz was measured to be 450° rather than 480° as predicted. This discrepancy was caused by the limited coupling range of the in house built VDC used in this experiment $(x_{max} = 0.9)$. It is anticipated that improving the VDC coupling performance would achieve the full 480° phase shifting range.

In comparison with the VSPS, the SO-VSPS trades off its bandwidth for the extension of phasing range. The SO-VSPS bandwidth is inherently limited by the device resonances at $f_{\rm res}$ and $3f_{\rm res}$. The SO-VSPS is thus not suitable for applications requiring more than an octave bandwidth.

Similar to the VSPS, the SO-VSPS is also subject to polarization and bias drift [7]. It is thus very critical that the polarization at the output of the FIPS is maintained and aligned well with the required polarization of the VDC device. Misalignment of the carrier polarization can result in the carriers from different arms of the FIPS exhibiting different losses through the VSPS. This consequently alters the phase and the amplitude responses through the SO-VSPS. It is anticipated that implementing the whole system using polarization maintaining components could significantly improve system stability and allow further simplification of the phase shifters through the removal of polarization controllers.

A previous publication has compared the microwave and photonic implementations of the VSPS [12]. It was found that the bandwidth of the electronically realized VSPS was significantly limited by the mixer bandwidth. Photonic realization of the device was therefore investigated. By employing photonic techniques, signal processing functions such as splitting or delaying of the RF signals are frequency invariant within the microwave bandwidth since the fractional RF bandwidth at the optical frequency is negligibly small. It is also proposed that a compact integrated optics form of the SO-VSPS device should be conceived to realize a cost effective phase shifter.

In the demonstrated system, manual adjustments of the MZM and VDC biases were required to set the system phase response. It is proposed that electronic monitoring and controlling of the bias states of these components should be considered if the system were to be used in a practical application. A simple electronic circuit with several servo control loops could be used to stabilise the system and to counter bias drift. Simple and rapid phase adjustments could also be achieved by implementing a phase setting algorithm, such as the two stage setting technique proposed in the previous section.

V. CONCLUSION

A novel technique has been proposed to extend the available phasing range of the VSPS by exploiting its second order response. This was achieved by offsetting the phase response of the VSPS so that its second order response mimics a TTD characteristic. Experimental results have verified that the device did behave as predicted. The SO-VSPS has extended the phasing range of the VSPS from 0–120° to 0–480°, but reduced its bandwidth to within the second order band. This phase shifting range is sufficient for steering a four element PAA 30° off broadside.

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