The constant and the $f^{0.5}$ term dependence on temperature are shown in Fig. 2. The constant term is seen to increase significantly against temperature, while the $f^{0.5}$ term increases nearly linearly with frequency. For plotting purposes, we approximate the temperature dependence of $b(T)$ as T^2.

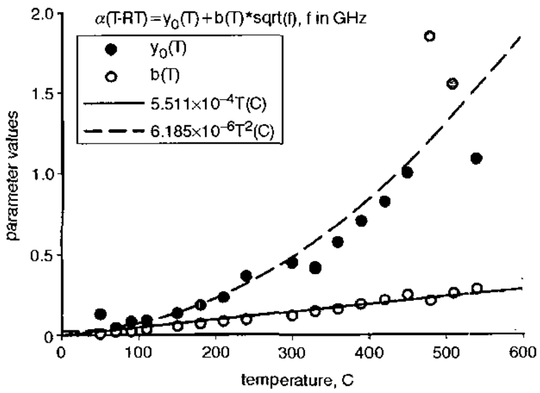

Fig. 2 *Extracted parameter values y_0 and b of (2) for the frequency dependent increase in attenuation of CPW lines against temperature*

These results indicate that SiC wireless circuits may be made on SiC wafers for operation at high temperatures, but at 500°C, the attenuation of microwave transmission lines will increase by approximately 3.25 dB/cm at 50 GHz and 2 dB/cm at 1 GHz. Although further analysis is required, we reason that the major cause for this increase in transmission line attenuation appears to be due to a decrease in the SiC resistivity [1].

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Wideband RF photonic vector sum phase-shifter

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A novel broadband linear phase phase-shifter based on the vector summation method is proposed. A photonic implementation of the phase-shifter with a continuously variable linear phase-shift up to 120° over the frequency range of DC–4 GHz is demonstrated. Good agreement between the measured responses and theoretical predictions is obtained.

Introduction: In many advanced defence and radio astronomy applications there is an increasing demand for instantaneous wideband phased array systems. The steering of such phased array systems is often achieved using true-time delay (TTD) units for the broadband beam squint-free operation.

There are many papers describing photonic implementations of TTD devices, e.g. [1, 2]; however their application in practical systems is limited due to their complexity and cost.

A variable feedback photonic phase-shifter (VFPPS) was developed recently and showed that it is possible to achieve phase-shifts that are approximately linear with respect to frequency [3]. The VFPPS operates by coupling light into a resonant feedback loop. The VFPPS that exhibited variable phase-shifts through the application of a biasing voltage was demonstrated from DC to 1.2 GHz [3].

For the device to operate at higher frequencies, the size of the optical feedback loop must be reduced to less than half a wavelength at the highest RF operating frequency. In turn, this puts tremendous pressure on the tolerance and yield of the fabrication process.

In this Letter, we overcome the inherent difficulties posed by the VFPPS by proposing a new phase-shifting device that operates on the principle of vector summation [4, 5]. The proposed device alleviates the difficulties by eliminating the small optical waveguide loop while maintaining similar performance to the VFPPS, thereby allowing it to operate in the baseband with high cutoff frequencies.

Principle of operation: Fig. 1 shows a block diagram of the proposed broadband phase-shifter using the vector summation method, hence named vector sum phase-shifter (VSPS). The expressions in the square brackets indicate the magnitude and phase of the RF signals at various stages in the VSPS.

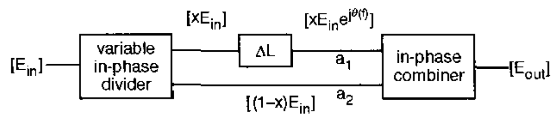

Fig. 1 *Schematic block diagram of broadband VSPS*

From Fig. 1, the transfer function of the VSPS is expressed as

$$H(f) = a_1(1-x) + a_2 x e^{j\theta(f)} \tag{1}$$

where $\theta(f) = -2\pi f n \Delta L/c$ and ΔL is the path length difference between the two arms; n is the refractive index of the delay lines; c is the velocity of light; a_i ($i = 1, 2$) is the individual attenuation (if any) of the arms.

From (1), the minimum phase-shift through the VSPS is zero and the maximum phase-shift through the device is $\theta(f)$. Other phase-shifts in the range between these two values can be obtained by intermediate values of x between 0 and 1. The VSPS therefore behaves like a continuously variable frequency linear phase-shifter.

Like the VFPPS in [3], cancellation of the RF signal from the two distinct paths of the VSPS happens at the device resonant frequencies, which are defined as $f = (m + 0.5)c/(n\Delta L)$ for integer m. Near to these resonant frequencies, the VSPS transfer function exhibits a high loss and poor phase linearity. As such the usable device bandwidth is limited to well below the lowest resonant frequency.

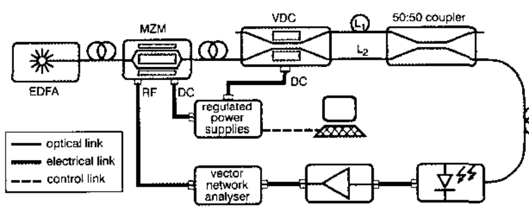

Fig. 2 *Photonic VSPS experiment setup*

Photonic vector sum phase-shifter: To verify the VSPS concept, a photonic implementation of VSPS was prototyped and characterised. The experiment setup is illustrated in Fig. 2.

The photonic implementation of the VSPS is based on the intensity modulation and direct detection technique (IM/DD). Since the VSPS resembles a Mach-Zenhder interferometer, utilising a narrow linewidth laser can result in coherent interference when combining the two optical paths. To avoid the degradation of the photonic VSPS transfer function due to the coherent interference, the amplified spontaneous emission (ASE) of the erbium-doped fibre amplifier (EDFA) has been used for the optical carrier. Other means of avoiding coherent interference have been developed, but these will be reported elsewhere.

The optical carrier is modulated using a commercial 10 GHz Mach-Zehnder modulator (MZM). The modulated optical signal is then split by a variable directional coupler (VDC). The VDC was fabricated on $LiNbO_3$ and exhibits a switching voltage of 1.8 V. The optical delay lines L_1 and L_2 were formed using singlemode fibres cut to the length of 1038 and 1020 mm, respectively. The modulated optical signal was combined through a 50:50 fibre coupler before being demodulated with a wideband photodetector.

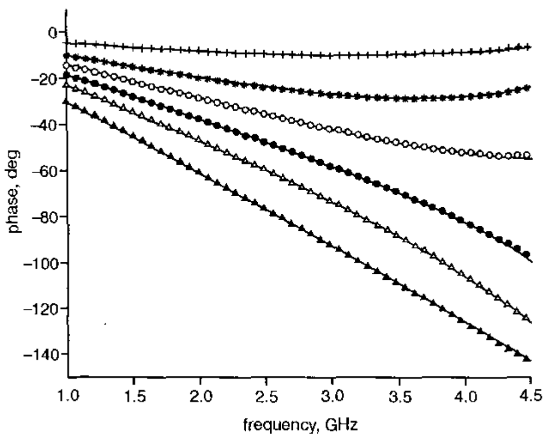

Fig. 3 *Measured (points) and predicted (solid lines) phase response of photonic VSPS for various x values, taking $x=0$ as reference*

+ $x=0.16$ (0.1 V)
* $x=0.35$ (0.5 V)
○ $x=0.48$ (0.7 V)
• $x=0.605$ (0.9 V)
△ $x=0.73$ (1.1 V)
▲ $x=0.93$ (1.7 V)

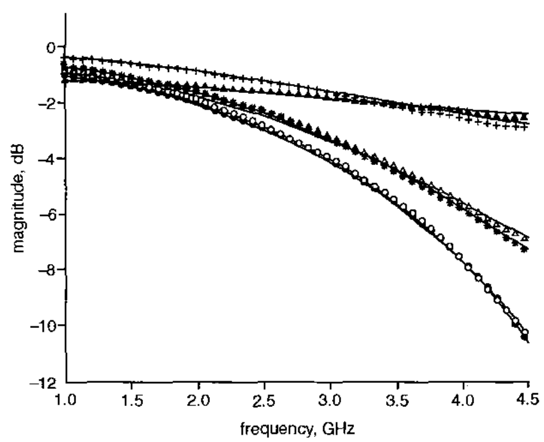

Fig. 4 *Measured (points) and predicted (solid lines) magnitude response of photonic VSPS for various x values, taking $x=0$ as reference*

+ $x=0.16$ (0.1 V)
* $x=0.35$ (0.5 V)
○ $x=0.48$ (0.7 V)
• $x=0.605$ (0.9 V)
△ $x=0.73$ (1.1 V)
▲ $x=0.93$ (1.7 V)

Figs. 3 and 4 show the measured (points) and predicted (solid lines) phase and magnitude of the photonic VSPS for various VDC splitting ratios. These results were taken by calibrating the forward transmission coefficient of the vector network analyser when the photonic VSPS was set to $x=0$. The value in brackets shows the VDC biasing voltage, which was changed over the switching voltage range of the VDC (1.8 V). The phase linearity with frequency is obvious up to 4 GHz for all x values. The phase-shifting range at 4 GHz is more than 120°. The frequency dependent amplitude imbalance varies from 0 dB (when $x=0$; 1) to 12 dB (when $x=0.54$). The reason that maximum amplitude imbalance does not occur at $x=0.5$ is because the longer arm has 0.6 dB more optical loss than the other arm. This optical loss difference was due to the used fibre splicing technique, which could be improved. In addition to shifting the resonance from $x=0.5$, the optical loss difference between the two arms also caused an increasing insertion loss for x values close to 1, as observed in Fig. 4. It can be seen that good agreements between the experiment and theory were obtained.

Practical implications in phased array antennas: The advantage of the photonic VSPS lies in the integration of its components, which allows for low cost and compact phasing solutions to be attained in practical systems. However, the phase-shifting range is limited to around 120°. It is obvious that this phase-shifting range is very limited for phased array applications where large phase-shifts may be required to steer the radiating beam. This issue has been addressed for the previously reported VFPPS and can be equally employed for VSPS. These approaches feature cascading multiple devices [6] or cascading the device with switched delay lines [7].

Although, the VSPS exhibits approximately linear phase response, it suffers relatively large amplitude imbalance, which may distort the antenna array beam pattern shape. To improve VSPS, techniques to increase phase-shifting range and to reduce amplitude imbalance are to be investigated.

Conclusions: A novel broadband linear phase phase-shifter based on the vector summation method is proposed. A VSPS was demonstrated in photonic form and operated from DC to 4 GHz. Improvements of the device phase-shifting range and amplitude imbalance may be needed for practical phased array systems and were identified for future investigations.

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