3-D Printed Variable Phase Shifter

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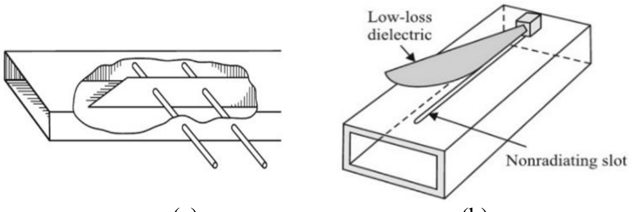
***Abstract*—This letter presents the first fully 3-D printed microwave variable phase shifter. The design methodology for a 3-D printable dielectric flap metal-pipe rectangular waveguide variable phase shifter is described. The ABS building material was independently characterized, revealing a dielectric constant of 2.34 and loss tangent of only 0.0015 at 10 GHz. The predicted and measured performance is given, demonstrating a maximum relative phase shift of 142° at 10 GHz, with a near uniform relative phase shift across the whole of X-band and a low variation in differential-phase group delay.**

***Index Terms*—3-D printing, additive manufacturing, FDM, metal-pipe rectangular waveguide, phase shifter, X-Band.**



(a) (b)

Fig. 1. Illustrations of two 3-D printable variable phase shifter approaches for metal-pipe rectangular waveguide technology [2]: (a) tapered dielectric slab with moving rods; (b) curved dielectric flap inserted in the non-radiating slot.

I. INTRODUCTION

WITH phase steered phased-array antennas, true phase shifters are added to the feeds of array elements. Waveguide phase shifters are often based on a ferrite technology [1]. These are usually expensive, due to the costs associated with the materials and fabrication, and also have a significant weight penalty. Another class of waveguide phase shifter is dielectric-based [2], [3]. These can be substantially cheaper and lighter, although they are mechanically controlled.

Over the past two decades, 3-D printing (also known as additive manufacturing) has found widespread applications in rapid prototyping and manufacturing of high geometrical complexity components; this offers the possibility of replacing components on-site, which may be critical in remote or hard to access locations and/or when the lead time is a limiting factor.

3-D printed metal-pipe rectangular waveguides (MPRWGs) and associated filters have been demonstrated over the past four years [4]–[7]. In this letter, we demonstrate the first variable phase shifter, with all parts being 3-D printed.

II. DESIGN

The simplest method of realizing a variable waveguide phase shifter is through the insertion of a dielectric slab. This changes the effective relative permittivity within the waveguide section containing the dielectric slab. As a result, the guided wavelength for the dominant TE$_{10}$ mode $\lambda_g = \lambda_o/\sqrt{\varepsilon_{eq} - (\lambda_o/2a)^2}$ changes; where λ_o is the wavelength in free space, ε_{eq} is the effective relative permittivity within the section of waveguide containing the dielectric insert, such that $1 < \varepsilon_{eq} < \varepsilon_r$; ε_r is the dielectric constant of the dielectric insert (i.e. either a slab or flap); and a is the internal broad wall dimension of the waveguide. Inserting a dielectric slab/flap decreases the guided wavelength and increases the transmission phase of the wave passing through a fixed length of waveguide section. Several possible configurations employing low loss dielectric slab/flaps are possible [8]–[12]. These either require waveguide section switching or an actuator to physically move the dielectric slab/flap. 3-D printable waveguide phase shifters that employ dielectric slabs [2] and flaps [2], [3], are illustrated in Fig. 1.

Due to its simpler design and ease of tuning, the dielectric flap was chosen for the work presented in this letter. The slot is in the center of the broad wall of the waveguide, where the E-field is at its maximum, to achieve the greatest possible phase shift while also minimizing radiation losses. As the penetration depth increases the effective permittivity in the waveguide section increases, creating a larger phase shift.

The maximum relative phase shift achievable for a dielectric-flap phase shifter is dependent on the length of waveguide section and also the flap's profile, thickness and dielectric constant. The maximum length of the phase shifter is limited by the 3-D printer's build volume. Using an entry-level desktop 3-D printer [7], the waveguide and slot lengths were designed to be 150 mm and 100 mm, respectively. The flap was printed from acrylonitrile butadiene styrene (ABS), which were expected to have a dielectric constant $\varepsilon_r = 2.54$ and loss tangent $tan\delta = 0.0151$ at 10 GHz [15]. This left the profile and thickness t_f of the flap as the remaining design parameters. A circular arc profile was chosen, so that the curvature would be the same at any depth of insertion, in order to minimize

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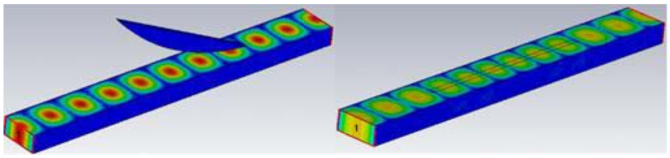

(a) (b)

Fig. 2. Simulated E-field pattern in the waveguide: (a) with the flap removed (25º flap angle); and (b) with the flap fully inserted (0º flap angle).

reflection losses. A 130 mm radius of curvature allows the flap to reach (i.e. touch) the full depth of the waveguide, when fully inserted. To avoid excitation of higher-order modes [13], [14] and minimize radiation losses from the slot, the dielectric flap must be kept relatively thin (i.e. $t_f \lesssim a/7.5$). To find the optimal thickness, electromagnetic simulations were performed using CST Microwave Studio; resulted in an optimal slot width of $t_f = 3$ mm. Fig. 2 shows the resulting simulated E-field patterns within the optimal design at 10 GHz when the flap is removed and when fully inserted. It can be seen that when the dielectric flap is fully inserted an extra half-guided wavelength is approximately introduced into the section of waveguide. Simulations at 10 GHz predict a maximum relative phase shift of 143° when the flap is fully inserted (i.e. with a flap angle equal to 0°).

III. FABRICATION

For manufacturing, fused deposition modeling (FDM) additive manufacturing with copper electroforming/electroplating technologies was chosen, as this combination has already been shown to create low loss X-band waveguides; comparable in performance to commercially machined waveguides, but with significant reductions in both cost and weight [7].

A desktop 3-D printer (Makerbot Replicator 2X [7]) was used with ABS building material. The machine was setup with a 1 mm wall thickness, 10% infill and 100 μm layer height for printing the waveguide and a theoretical infill of 100% for the dielectric flap. The 15 cm long waveguide was built-up along the direction of propagation, while the flap was inverted and built-up towards the curve. After printing, the waveguide was electrolessly plated with a 3 μm nickel seed layer and then electroplated with a 27 μm copper layer, which is in excess of five skin depths at X-band. Finally, the two separate pieces were assembled by clicking the dielectric flap into the bracket.

IV. MEASURED RESULTS

All measurements were undertaken at the UK's National Physical Laboratory, using an Agilent PNA-X Vector Network Analyzer (VNA) with X-band waveguide adapters. A Thru-Reflect-Line (TRL) calibration technique was used to calibrate the VNA. The ABS building material was independently characterized, revealing a dielectric constant of 2.34 and loss tangent of only 0.0015 at 10 GHz. The variable phase shifter was measured using the setup shown in Fig. 3. A 1.77 mm diameter pin, oriented perpendicular to the longitudinal axis of the slot, was used to determine the dielectric flap angle during the measurements.

Fig. 3. Experimental measurement setup for the variable phase shifter.

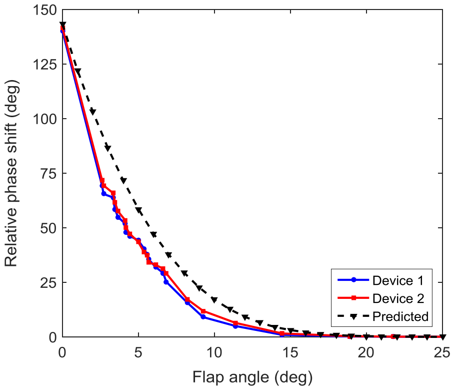


Fig. 4. Predicted and measured relative phase shift at 10 GHz against dielectric flap angle.

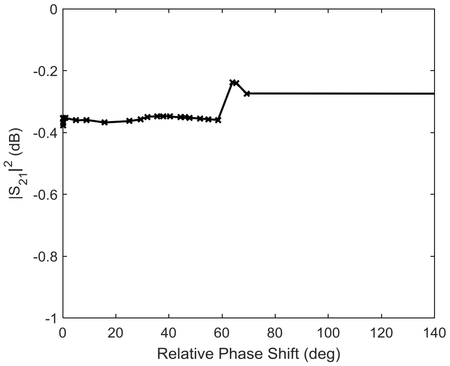
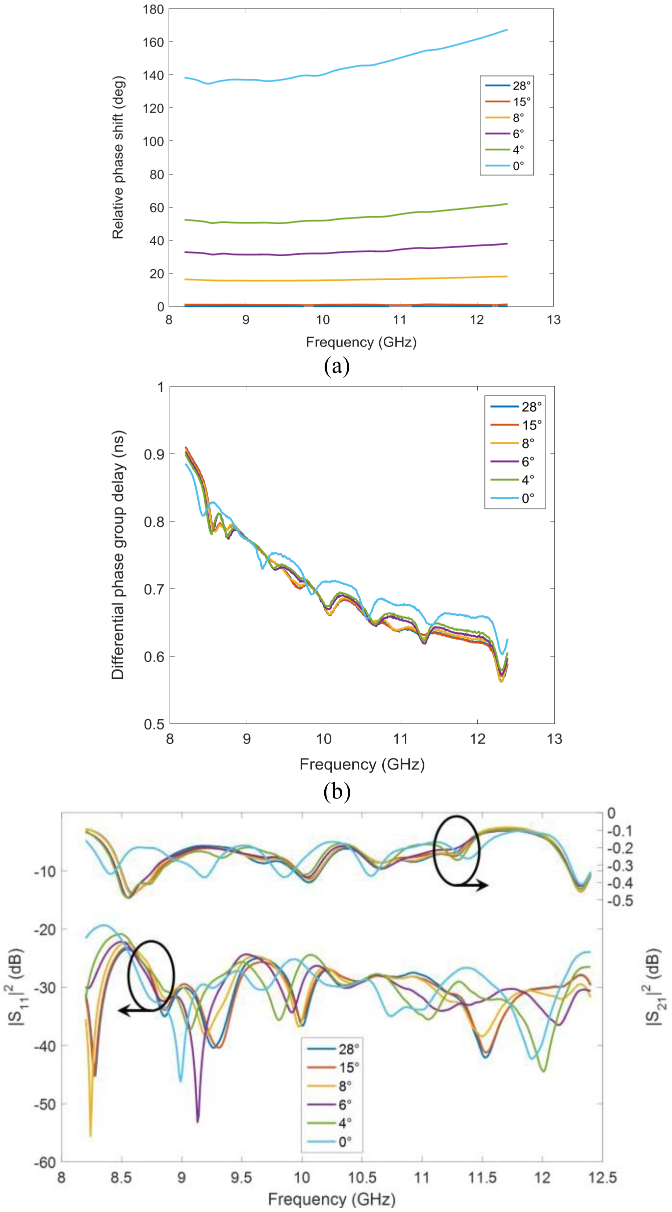


Fig. 5. Measured transmission for different relative phase shifts at 10 GHz, indicating a worst-case PM-AM conversion of ±0.1 dB across the whole tuning range.

Fig. 4 shows the predicted and experimentally measured performances of two fabricated phase shifters at 10 GHz. It can be seen from the experimental results that a relative phase shift of $\sim 142°$ is achieved when the dielectric flap is fully inserted; the tuning behaviour was found to be consistent for the two identical prototype devices. The discrepancy between the predicted and experimental results can be attributed to uncertainties associated with the measured flap angle. The measured PM - AM conversion is shown in Fig. 5.

Fig. 6(a) shows the measured relative phase shift across X-band for one of the two proof-of-concept devices. It can be seen that there is a relatively flat phase shift across the whole of X-band. Design iterations would allow this to be further optimized. Fig. 6(b) shows that there is only a small variation in differential-phase group delay.



(a)

(b)

(c)

Fig. 6. Measured phase shifter performance across X-band for flap angles of 0°, 4°, 6°, 8°, 15°, 28°: (a) relative phase shift; (b) differential-phase group delay; and (c) insertion and return loss.

We previously demonstrated that for the solid waveguide (without the slot), made using the exact same manufacturing process, the dissipative attenuation ranges between 0.2 and 0.6 dB/m, with a worst-case return loss of 32 dB, across X-band [7]. Therefore, our 15 cm long waveguide was expected to have a minimum attenuation of between 0.03 and 0.09 dB. Fig. 6(c) shows the measured insertion loss and return loss performances for the maximum and minimum dielectric flap angles. It was found, for all flap angles and across the whole of X-band, that the worst-case levels of insertion loss and return loss were 0.49 dB and 19 dB, respectively.

V. CONCLUSION

In this letter the design, manufacture and measured performance of two identical 3-D printed microwave variable phase shifters has been shown for the first time. The dielectric flap phase shifter shows excellent performance, having a maximum relative phase shift of 142° at 10 GHz and worst-case insertion loss of 0.49 dB across the whole of X-band. A greater tuning range can be achieved by increasing the dielectric constant and/or length of the flap. These results demonstrate the real potential for realizing high performance, low cost and light weight microwave metal-pipe rectangular waveguide components and subsystems using 3-D printing rapid prototyping manufacturing. In principle, actuation mechanisms (e.g. screw threads) and packaging can also be 3-D printed, opening up many possibilities for a diverse range of future applications. Moreover, this new manufacturing technology offers many new opportunities for part replacements in remote/hostile locations using precision rapid prototyping.

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