Characteristics of Ka Band Waveguide using Electromagnetic Crystal Sidewalls

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Abstract — **Electromagnetic Crystal structures have been used as sidewalls in special waveguides 30 to 40 GHz. This has the effect of substituting a high impedance surfaces in place of the normal conducting metal sidewalls. The objectives in so doing are to obtain uniform electric field across the width of the waveguide and to force the wave in the guide to adopt the nature of a TEM wave. Insertion loss of Ka Band waveguides has been measured. The measurements indicate that insertion loss is low. The dependence of transmission phase on the center frequency of sidewall resonance has been measured and indicates that tunable sidewall resonance will provide simple and low loss phase shifting systems.**

I. Introduction

A special form of waveguide that has been developed will be particularly useful for millimeter wave array systems tasked to provide agile beam steering and moderate to high levels of power. First proposed in the context of array amplifiers [1]. The modified system is a rectangular waveguide in which the sidewalls have been replaced by an electromagnetic crystal (EMXT), which presents a high impedance surface at the sidewall in place of the normal perfect conductor sidewall. Prior realizations of this type of guide with non-zero sidewall impedances have demonstrated, at Ku band, that the electric field is made uniform across the guide width and that the insertion losses were low at Ku Band.[1] This work extends the demonstration of these guides to frequencies between 35 and 40 GHz and introduces phase shifting using these structures.

II. Theory

The initial high impedance surfaces were developed by Sievenpiper [2]. These were of a type that presented a surface which reflected a EM wave with a reflection coefficient of +1 over the band of interest irrespective of the direction of E field polarization. Their effect of converting the TE10 guide mode into a TEM guide mode was demonstrated in Ku Band waveguide [3]. The polarization sensitive EMXT surfaces of this work are composed of a thin dielectric substrate which is metallized completely on one side and has stripes of metal separated by narrow gaps on the other side. (Fig.1)

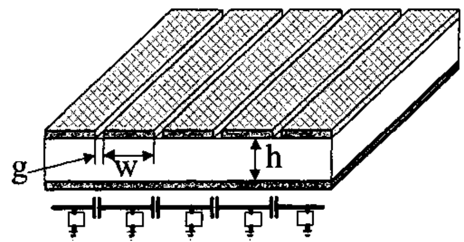

Figure.1 Physical form of the Stripe EMXT.

The substrate may be any low loss microwave substrate. Gap 'g' provides the capacitance of a parallel tank circuit to an incoming wave the E field of which is normal to the stripe. The substrate thickness 'h' and the stripe width 'w' provide inductance to ground which is effectively in parallel with the gap-capacitance. At a certain resonant frequency, Fr, the incoming wave is reflected with a $1.0\angle 0°$ coefficient. The orthogonal wave, with E field along the stripes, is reflected as from a normal metal.

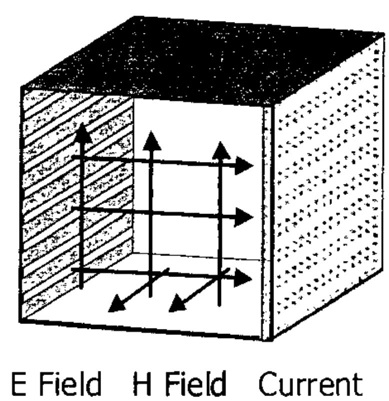

Fig.2 The EMXT waveguide which will support a TEM mode.

Figure 2 illustrates the form of an EMXT waveguide. The sidewalls are replaced by the EMXT structure of Fig.1, making for a totally metal enclosed pipe but with the inside surface of the sidewalls inhibited from carrying current

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in the vertical direction. A TEM wave will carry power through this pipe because the necessary currents can flow in the top and bottom surfaces.

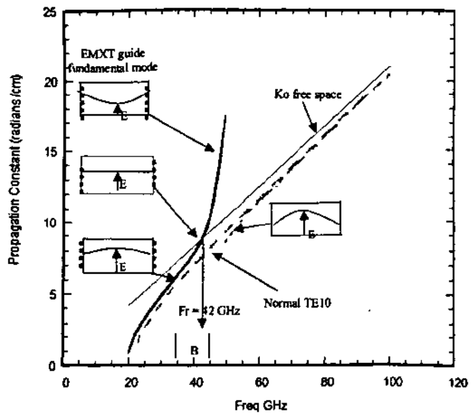

Fig.3 Propagation in EMXT waveguide

Figure 3 illustrates the propagation constant (β) of the EMXT guide. Propagation in free space and propagation in a normal metal sidewall guide are also depicted by the thin and the dashed lines respectively. The full line shows the propagation of the fundamental mode in the EMXT guide. A 7mm wide guide is modeled with resonant sidewalls. The results are obtained by solving the boundary value problem, assigning a single resonant frequency of 42 GHz for the sidewall. The figure shows that when signal frequency coincides with the resonant frequency the propagation constant is that of free space and the fields (E and H) are uniform inside the guide. Power passes through the guide as a TEM wave. Below resonant frequency the sidewall becomes an inductive admittance and the fields relapse slowly to the TE10 half-sine with maximum field (center) being no more than twice minimum field (sidewall) over a bandwidth of 10%. This useful bandwidth depends on the design of the sidewall, particularly the thickness 'h'. Above the Fr the field at the sidewall begins to grow and the wavelength decreases rapidly until, eventually, the power is divided between two 'surface waves at the walls. The rate of this 'conversion' is also controlled by the design of the sidewall.

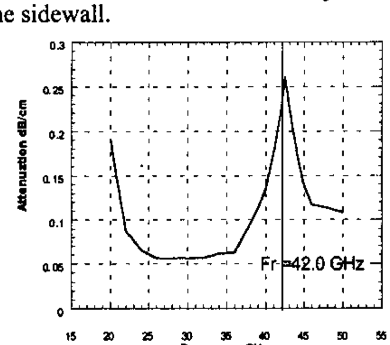

Figure 4 Attenuation in the EMXT guide

The useful bandwidth of the EMXT guide is also limited by attenuation, which is depicted in Figure 4. The computed attenuation is well-behaved until frequencies above resonance Fr, at which point wall current increases and attenuation rises sharply.

III Experimental EMXT High Impedance Surfaces

The waveguides of this work had a guide width of 7 mm as they were adapted from WR28 metal guide by the removal of the metal sidewalls and their replacement by the EMXT structures. This is illustrated in Figure 2. Initial Ka Band EMXT structures were fixed tuned; i.e., they did not contain tunable elements such as varactors, but had a fixed resonant frequency. These first EMXT surfaces were fabricated on Rogers Duroid RO3006 substrates of relative dielectric constant 6.15 and a loss tangent of 0.013 at 35 GHz. The substrates were 0.62 mm thick and copper coated on both sides, with patterns etched on one side. The patterns were slots that formed stripes on the inner sidewall of the waveguides as per Fig.2.

These high impedance surfaces are characterized by a simple measurement of the reflection coefficient. The reflection coefficient of a wave impinging with normal incidence on the striped surface and oriented so that electric field is across the stripes (as opposed to along same) will sweep through the high impedance regions of the Smith Chart. Fig.5 illustrates a reflection coefficient measurement for which the resonant frequency Fr value is 38.7 GHz. The bandwidth Δf of these EMXT high impedance surfaces is very dependent on the design of the structure. The high impedance can be closely modeled as a parallel inductance and capacitance. Increasing inductance (increasing 'h') and decreasing capacitance rapidly improves bandwidth and insertion loss. [2]

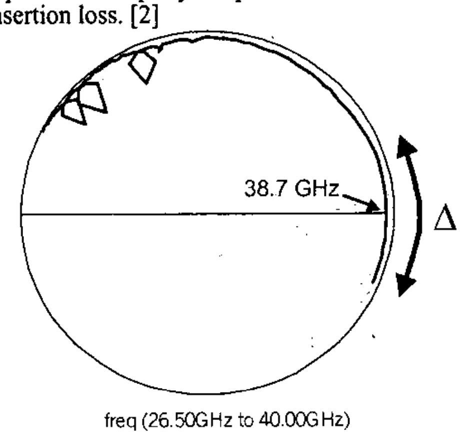

Fig.5 Reflection coefficient at a high impedance striped surface.

The measurement of Fig.5 shows a bandwidth (defined as the frequency band between -30° and +30°) of approximately 4 GHz. and is the bandwidth obtained from using a 0.62 mm substrate of Duroid with copper stripes separated by 200 microns slots. Bandwidths of up to 25% may be obtained by increasing inductance (increasing 'h') and lowering capacitance (opening 'g').

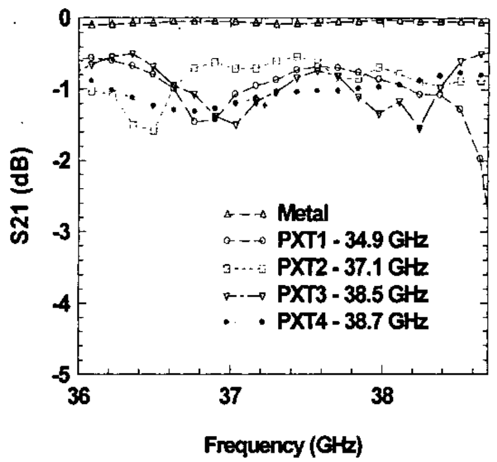

Fig.6 Insertion loss measurements in 2 cm guide length. Fr is varied.

IV. Waveguide Measurements

Insertion loss measurements were made of millimeter wave signals, at frequencies between 36 and 39 GHz, propagating through 2cm of EMXT waveguide. The insertion loss is shown in Fig.6 for guides in which the sidewall Fr values are varied from 34.9 GHz through to 38.7 GHz. The loss is approximately 0.5 dB per cm for the EMXT guides. The insertion loss is compared against that of an empty guide. This is a tolerable level of insertion loss and can be reduced by further design and materials optimization (e.g., reduction of loss tangent).

It is noticeable that the sharp rise of insertion loss, expected as operating frequency exceeds resonant frequency, is not apparent. This rise in insertion loss depends upon the onset of the "surface wave mode" above resonance, which triggers the increase in loss. A broadband high impedance surface, such as the Duroid samples measured, will delay the conversion to the sidewall surface waves and the high loss associated with that condition.

The attraction of this type of guide is based on the fact that propagation constant is a function of the Fr frequency. Vary Fr and the propagation constant curve of Fig.3 moves, causing rapid change of Beta the propagation constant and therefore of the phase of S21. This dependence may be assessed from the variation of the added phase of transmission in the EMXT waveguide. This 'added phase' quantity is the phase of S21 in the EMXT waveguide minus the phase of S21 in a metal walled waveguide. The added phase is shown in Fig.7 as a function of frequency, for the different Fr values in the 2cm guide. The added phase increases rapidly as Fr is driven substantially lower than operating (measurement) frequency. This behavior is in close accord with modeled performance of these waveguides in terms of phase control and insertion loss as predicted by the traditional boundary condition waveguide analysis methods. Figures 3 and 4 illustrated the modeled effects, which have been confirmed by finite element solvers.

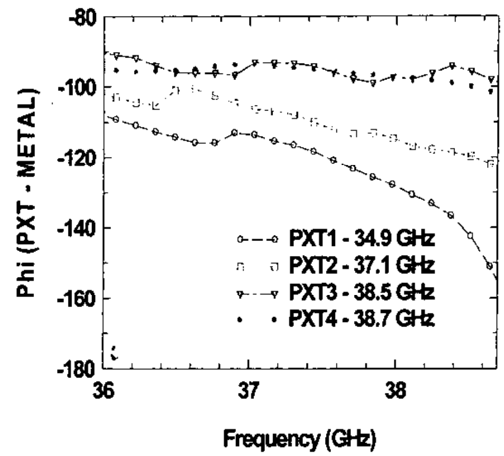

Fig.7 Phase shift of the 2cm guide as a function of sidewall resonant frequency Fr.

V. The Tunable EMXT Phase shifter

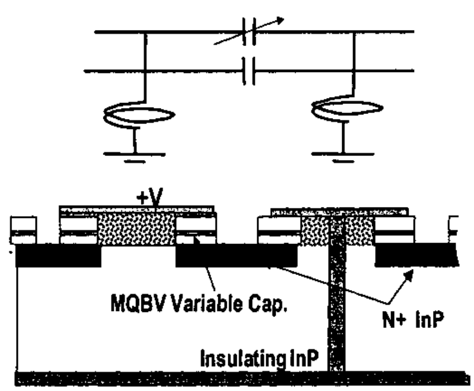

Fig.8 Cross section of an integrated gap varactor for tunable EMXT

The EMXT can be fabricated on substrates compatible with the realization of integrated devices; varactors for the special case discussed here. A variable capacitance was chosen to obtain a controlled and variable Fr in an EMXT. The InP Multiple Quantum Barrier Varactor was chosen for the variable capacitor and the EMXT was fabricated on a substrate of semi-insulating InP. The sketch in Figure 8 illustrates a cross section of the device used to vary gap capacitance. The EMXT employing the varactor gap was designed to provide an Fr that would vary from 30 GHz through 40 GHz for an applied bias between 0 Volts and 10 Volts. Polarity of bias was not critical since the MQBV exhibits an even function of C (pF) versus V.

The EMXT was installed into a 7 mm wide guide (WR28) over a length of 13 mm. The varactor provided the correct capacitance but exhibited an anomolously high series resistance of close to 3 ohms which would give rise to high loss at frequencies near Fr. These high losses notwithstanding, the EMXT waveguide was measured as a phase shifting device.

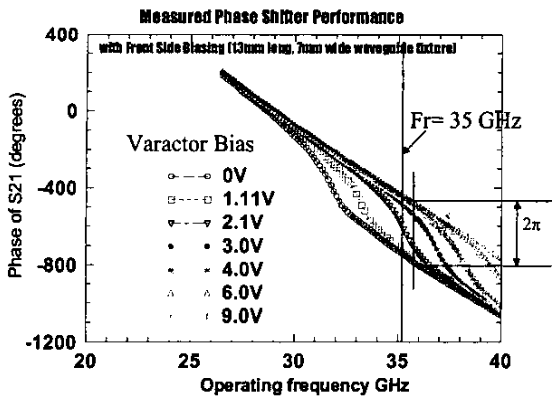

Fig.9 Control of phase achieved with an MQBV based EMXT

Figure 9 illustrates the measured control of the Phase of S21 through that length of guide. The figure reveals that the Fr is varied over the intended range and that phase control is also attained over that entire range. The phase change achieves a near 2π shift over a narrow frequency range, approximately 3GHz, and that narrow frequency range can be varied over the entire 10 GHz from 30 to 40 GHz. The chart shows that a bias of 2 Volts will be the appropriate bias for operation in the vicinity of 35 GHz and that a voltage swing from 1 to 3 Volts will change phase by nearly 2π. The insertion loss in this demonstration was high, peaking at nearly 10 dB; and was due to the high resistance encountered in the varactor. This high resistance has been corrected in following designs, and the expected maximum loss is less than 2 dB in designs current being evaluated.

VI. Conclusions

EMXT waveguides of the type depicted in Figure 2 can be used as a phase shifting device in addition to the original intended use of housing a quasi-optic array amplifier and extracting the maximum amount of power from that amplifier. The losses are moderate and can be improved significantly over the loss exhibited by these demonstration samples. The key aspect of attaining performance is the implementation of a low loss tuning system which will vary Fr, the frequency at which the sidewall impedance is maximum.

The design and fabrication of EMXT waveguides in which the sidewall Fr values are continuously tuned, either by varactor systems built into the sidewall or by MEMs systems built into the sidewall, will provide, following optimization, phase shifting waveguides which will be compatible with the array amplifiers already demonstrated. Experimental results of such waveguides that are in development show promise of effectiveness and low loss. With design optimization it is possible to predict phase shift of 2π radians in less than 13 mm of guide at 38 GHz with losses less than 0.5 dB. These devices working with array amplifiers mounted will set an example of an innovative way to extract power performance from solid state amplifiers at mmWaves up to and over 100 GHz.

[1] J.A. Higgins et al, "The Application of Photonic Crystals to Quasi-Optic Amplifiers", IEEE Trans. on MTT Vol. 47. No.11, pp2139-2143.

[2] D. Sievepiper. PhD Thesis UCLA (EE) 1998.

[3] M. Kim, etal, "A Rectangular TEM Waveguide with Photonic Crystal Walls for excitation of Quasi-optic Amplifiers", Session TU3B-2, Tech Digest of 1999 IEEE Microwave Symposium , Anaheim CA