Low-Loss Monolithic Tunable Electromagnetic Crystal Surfaces with Planar GaAs Schottky Diodes

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***Abstract* — Monolithic tunable electromagnetic crystal (EMXT) surfaces based on semiconductor varactors has been designed and fabricated for various microwave and millimeter wave applications. In order to tackle the problem of high losses associated with this kind of tunable EMXT structures, a high-quality planar air-bridged GaAs Schottky (PAS) diode process has been developed and incorporated to produce low-loss monolithic tunable EMXT surfaces. Finite-element model indicates that analog waveguide phase shifter with EMXT sidewalls can achieve 360^{o} phase shift with less than 3 dB insertion loss. A backside-biasing scheme utilizing through substrate vias has also been developed. Preliminary EMXT reflection measurements show lower loss comparing with previously demonstrated tunable EMXTs. Because of the high cut-off frequency (above THz) of the GaAs Schottky diode, this EMXT technology may be readily extended to higher frequencies applications such as W-Band ESA.**

Index Terms – Electromagnetic crystal, Schottky diode, phase shifter

I. INTRODUCTION

Metal-dielectric structures with two-dimensional periodicity may provide useful electromagnetic boundary conditions in many microwave and millimeter wave applications. Because of the periodicity of this kind of electromagnetic structures, sometimes they are called electromagnetic crystal (EMXT). EMXT surface exhibits an artificial high surface-impedance at some resonant frequency so that it reflects an incident EM wave with a coefficient of $+1\angle 0^{o}$. The top and side views of two typical EMXT surfaces are shown in Fig.1. They contain a dielectric substrate with one side covered by metal ground plane and the other side covered by metal patches with a periodic pattern. Through-substrate vias are included in these structures to suppress substrate modes. The top structure in Fig.1 has a hexagonal pattern and shows high surface impedance for incoming waves with an E-field in any arbitrary directions along the surface [1]. The bottom structure in Fig.1 has a rectangular strip pattern and exhibits high surface impedance only for incoming waves with an E-field perpendicular to the metal strips long dimension [2].

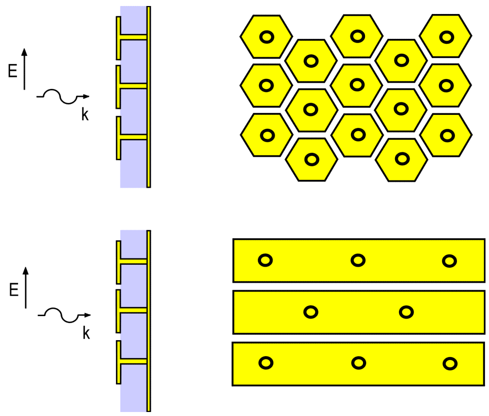


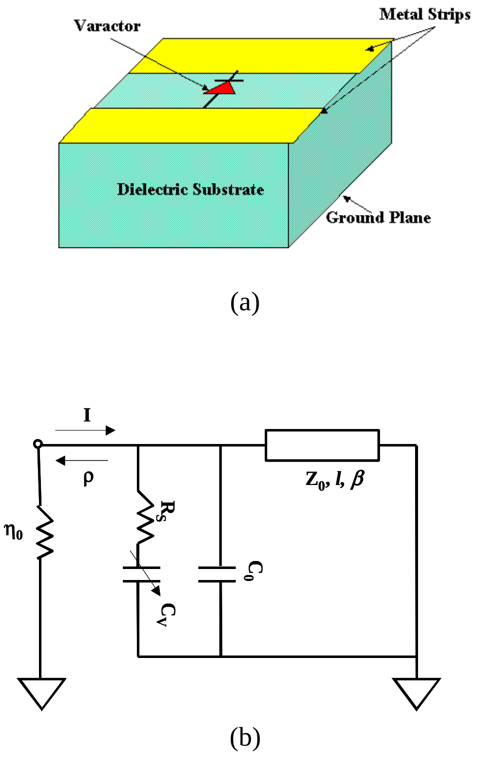
Fig. 1. Side and top view of EMXT structures with hexagonal metal patterns (top) and rectangular metal patterns (bottom).

Because of the unique high impedance at resonant frequency of EMXT surface and its ability to suppress surface waves, it has been used in various microwave and millimeter wave applications including low-profile antenna ground plane [3-4], mutual coupling reduction antenna ground plane [5], TEM waveguide [6-7], band-pass and band-stop filters [8-9], etc. With increased demand of modern systems for frequency and phase agility, EMXT surfaces with rapid tunability may have great potential in applications such as radar, sensors, and communications. InP heterostructure barrier varactor (HBV) tuned EMXT surfaces have been fabricated and used as sidewalls of a Ka-Band analog waveguide phase shifter [10-11]. When the bias voltage of the varactors is varied, the EMXT can be controlled to provide desired sidewall impedance. A two-dimensional Ka-Band phase scanned lens made of a 4 x 4 array of the InP HBV EMXT waveguide phase shifter has also been demonstrated [12]. However, due to the highly resonant nature of this kind of structures, RF losses are usually quite high around resonance and may hinder system performance. For example, the InP HBV tuned EMXT has shown maximum reflection losses of 7 dB at zero bias voltage and this translates to an analog phase shifter achieving 325° with a maximum loss of 10 dB (an average loss of 6 dB) at 38 GHz [11].

In this paper, a low-loss monolithic tunable EMXT surface based on high-quality millimeter wave planar air-bridged GaAs Schottky (PAS) diodes will be described. Optimized design of a Ka-Band full-wave analog phase shifter using finite-element model predicts an average insertion loss lower than 3 dB. Preliminary measurements of the fabricated PAS diode based EMXT have shown improvement of losses comparing with the previously demonstrated InP HBV based EMXT surfaces. An efficient biasing scheme through substrate vias and solder bumps has also been designed and verified. This simple and effective backside-biasing method may dramatically reduce the complexities in the interconnections and packaging of large-scale ESA.

II. EMXT DESIGN AND OPTIMIZATION

EMXT surface can be designed using a unit-cell approach due to its two-dimensional periodicity. The schematic drawing and an equivalent circuit model of a tunable EMXT unit cell (rectangular metal strip type) are shown in Fig.2.



(a)

(b)

Fig. 2. Schematic drawing (a) and equivalent circuit of a varactor tuned EMXT unit cell.

As shown in Fig.2a, parallel varactors are loaded in between each adjacent metal strips to provide the tuning mechanism. For an incoming plane wave with E-field oriented perpendicular to the metal strip, the equivalent circuit can be treated as a parallel circuit of a shorted transmission line, a parasitic capacitance C_0, and a variable capacitance C_V in series to a resistance R_S (diode parameters). The transmission line impedance Z_0 and propagation constant β are those of a plane wave in the media of the dielectric substrate while its length l is the substrate thickness. The shunt conductance, or the reverse bias leakage of the varactor is ignored here because the varactor quality factor Q is dominated by the losses resulting from the series resistance R_S.

For most applications involving tunable EMXT surfaces, especially phase shifter and electronically scanned antenna [11], it is very important to reduce RF losses. RF losses of this kind of surfaces can be characterized by measuring reflection loss of an incident EM wave. With good microwave dielectric used as substrate, the dielectric and conductor losses are usually negligible and the dominant losses come from the varactor series resistance R_S. According to the equivalent circuit shown in Fig. 2b, increasing the substrate thickness l and decreasing the varactor capacitance C_V reduces the loss of a tunable EMXT even though R_S increases ($C_V \bullet R_S$ remains constant to the first order. By reducing C_V the RF current flowing through R_S is reduced, hence lower losses can be achieved). However, because of the presence of the parasitic capacitance C_0 and fabrication limitations, a compromise between loss and tuning range has to be reached. To optimize the EMXT design, a finite-element model of the unit cell is used to accurately account for the existence of substrate vias and other parasitic components.

III. DEVICE FABRICATION AND CHARACTERIZATION

A picture of the fabricated PAS diode is shown in Fig. 3. The active diode epi-layer has a thickness of 250 nm and a doping density of $2x10^{17}$ cm^{-3}. An n^+ layer with a thickness of 5 μm and a doping density of $5x10^{18}$ cm^{-}3 is included below the active layer.

Since the series resistance R_S determines the RF loss and the parasitic capacitance C_0 limits the tuning range of EMXT surfaces, they are the primary factors considered while optimizing the diode structures. R_S mainly results from the undepleted portion of the active epi-layer, the n^+ region between the anode and the cathode, and the conductor loss in the narrow air-bridged finger of the anode. Thick layer of heavily doped n^+ material, shortened distance between anode and cathode, and shortened air-bridged finger all contribute to reducing R_S while reducing the overlap between the air-bridged finger and the cathode n^+ stack decreases C_0.

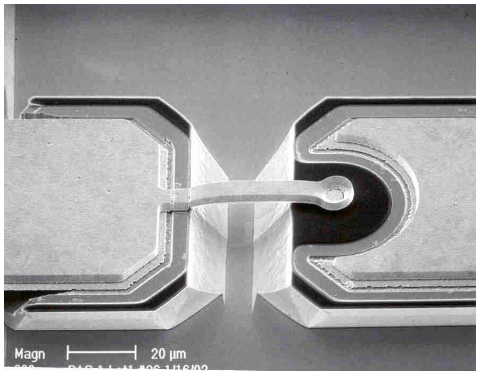


Fig. 3. A SEM picture of a fabricated PAS diode.

Both DC and RF characterizations of the PAS diode devices have been characterized. For RF performance, CPW test structures with the device mounted in shunt and series were measured up to 50 GHz using a HP 8510C network analyzer and on-wafer probes. For the 5.4 µm diameter diode used in this work, it was determined that a typical device had an ideality factor of 1.15, reverse break down voltage of 6.0 V (at 1 µA leakage current), forward-bias series resistance of 2.4 Ω. The measured RF properties of the PAS diode are compared with the InP HBV used in previous tunable EMXT surfaces in Table I. It can be seen that the PAS diode has a smaller varactor capacitance with a lower series resistance comparing with the InP HBV. This will lead to a much lower loss EMXT as explained in section II. The ongoing optimization of the fabrication process can potentially reduce the series resistance to even below 2 Ω.

Table I. Summary of InP HBV and PAS diode characteristics

	InP HBV	**GaAs Schottky Diode**
Device Size	**6 x 43 µm²**	**5.4 µm diameter**
Max Capacitance	**120 fF**	**49 fF**
Min Capacitance	**40 fF**	**26 fF**
Series Resistance	**3.0 Ω**	**2.3 – 2.7 Ω**
Cutoff Frequency	**440 GHz**	**1200 GHz**

IV. EMXT FABRICATION AND CHARACTERIZATION

A monolithic EMXT surface integrated with 5.4 µm PAS diodes described in the previous section has been fabricated on 254 µm (10-mil) thick semi-insulating GaAs substrate. Fig. 4 is a SEM picture of the GaAs EMXT surface.

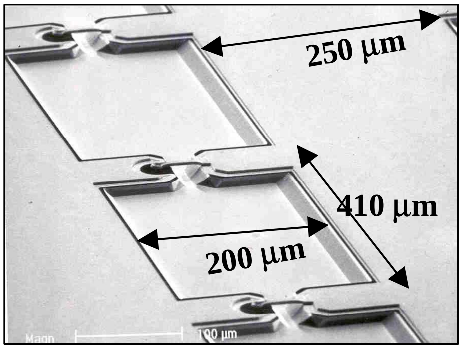
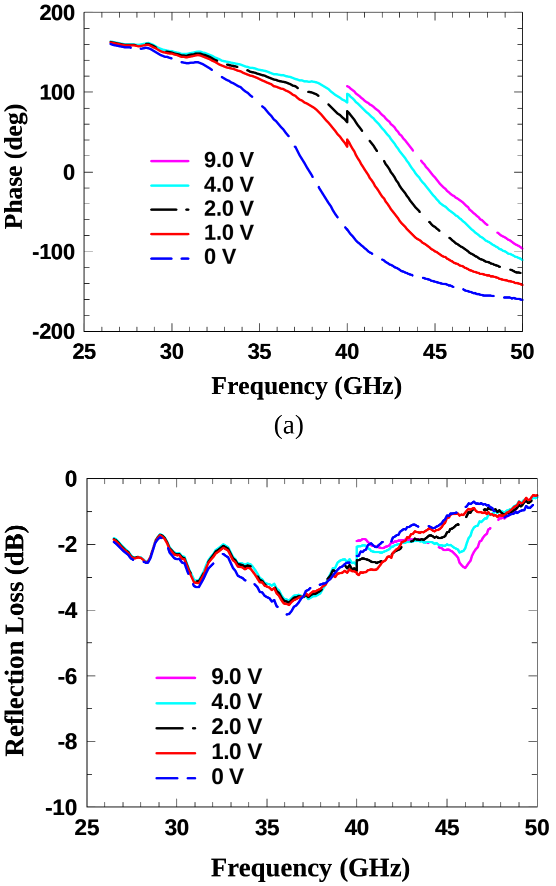


Fig. 4. A SEM picture of the GaAs tunable EMXT structure.

The metal strips of the EMXT have a width of 250 µm and the gap between adjacent strips is 200 µm. The periodicity of the Schottky diodes is 410 µm. The design is optimized to achieve a Ka-Band full-wave waveguide phase shifter with minimum insertion loss. Finite-element model predicts that a 2π analog phase shifter (10mm long guide with an aperture of 3mm x 3mm) with an average insertion loss of 2 dB should be realizable for a diode R_S of 2 Ω (comparing to an average loss of at least 6 dB for the InP based EMXT surfaces).

Reflection measurements have been done to characterize the first fabricated EMXT. Preliminary data plotted in Fig.5 show that for a bias voltage from 0 to 9 Volts, resonant frequency (at which the reflection coefficient has a 0^o phase) is tuned from 37.8 GHz to about 45 GHz and the maximum reflection loss is around 4 dB (3 dB lower than that measured for InP HBV EMXT). Optimization of the PAS diode EMXT fabrication process is being implemented to further reduce loss.

Another improvement of the GaAs tunable EMXT reported in this paper is the backside-biasing scheme. Ten-mil thick GaAs substrate via and solder pad processes have been developed and successfully tested. This backside-biasing scheme may greatly simplify the interconnection and packaging problems for electronically scanned antennas with large number of elements.



(a)

(b)

Fig. 5. Measured reflection phase (a) and magnitude (b) of a PAS diode based EMXT. The small discontinuity at 40 GHz is due to different calibration kits of the network analyzer.

V. CONCLUSION

Monolithic tunable EMXT surfaces at Ka-Band using high-quality PAS diodes have been fabricated. The diodes are designed for lower series resistance and parasitic capacitance. Preliminary results show improvement in loss comparing with previously fabricated InP HBV based tunable EMXT surfaces. A backside-biasing scheme using substrate vias has also been developed. Low-loss tunable EMXT surfaces with simple biasing circuitry may be suitable for many microwave and millimeter wave applications, especially electronically scanned antennas. Because of the high cut-off frequency of the diode devices, this tunable EMXT technology can be extended to higher frequency such as W-Band.

ACKNOWLEDGEMENT

The authors wish to thank Dr. J. B. hacker and Dr. D. M. Pilz at Rockwell Scientific Company for useful technical discussions.

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