Electromagnetic Crystal (EMXT) Waveguide Band-Stop Filter

Hao Xin, Aiden Higgins, Jonathan Hacker, Moonil Kim, and Mark Rosker

***Abstract*—An electromagnetic crystal (EMXT) with a bandgap around 35 GHz is used as the top and/or bottom walls of a rectangular waveguide. Because of its bandgap, such an EMXT waveguide is a very effective band-stop filter with the rejection band centered at 35 GHz. More than 70 dB of isolation for the rejection band and less than 2 dB of insertion loss for the pass band are measured. Finite element simulation of the EMXT band-stop filter agrees very well with measurements. Using tunable EMXT walls, a band-stop filter with adjustable center frequency and bandwidth can also be realized.**

***Index Terms*—Band-stop filter, electromagnetic band gap, electromagnetic crystal, waveguides.**

I. Introduction

ELECTROMAGNETIC crystals (EMXT), also known as photonic bandgap crystals when used in optical applications, are periodic electromagnetic structures. The term "bandgap" has its origin in the "band-stop" characteristic of transmission through or along these surfaces. EMXTs exhibit this rejection band at a "resonant frequency." The type of EMXT discussed here provides a high impedance surface at the resonant frequency; such surfaces are very useful in many microwave and millimeter wave components and systems, such as antenna ground planes [1], [2], TEM waveguides [3]–[5], and bandpass filters [6]–[8]. The high surface impedance EMXT with tunable resonant frequency has also been realized recently for both microwave [9] and millimeter wave applications [10]. Tunable surface EMXTs may be very attractive for many EM applications since they can provide controllable arbitrary surface boundary conditions. A Ka-band waveguide phase shifter with tunable EMXT surface replacing metal sidewalls of a rectangular waveguide has been built [11]. A 4×4 Ka-Band phased array using the EMXT waveguide phase shifter as both the phase-shifting and radiating elements has also been demonstrated [12].

In this letter, we will present a novel waveguide band-stop filter using the high surface impedance EMXT as the top and bottom walls of a rectangular waveguide. A prototype band-stop filter made using a surface EMXT with a fixed high surface impedance "bandgap" around 35 GHz is demonstrated. The EMXT wall resonant frequency and bandwidth determine the center frequency and bandwidth of the filter. We will also discuss band-stop filters of electronically adjustable center frequency and bandwidth using tunable EMXT surfaces.

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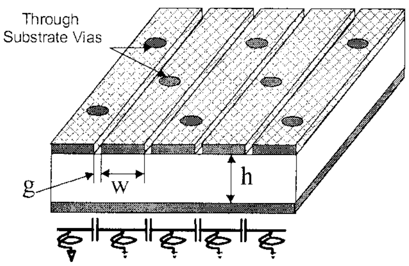
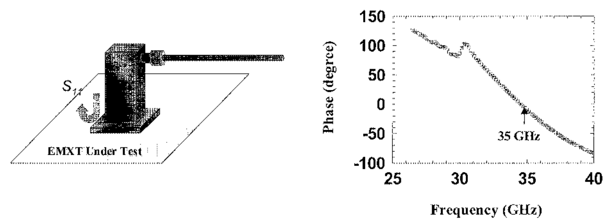


Fig. 1. Geometry of the striped-electromagnetic crystal (EMXT).



(a) (b)

Fig. 2. (a) EMXT characterization by reflection measurement. (b) Measured reflection phase as a function of frequency for the EMXT used in this work. This EMXT has a resonant frequency around 35 GHz.

II. EMXT Waveguide Band-Stop Filter

A. EMXT Surface

The EMXT used in this paper is composed of a thin dielectric substrate that is metalized completely on the backside as the ground plane and has stripes of metal separated by narrow gaps on the front side (Fig. 1). Rogers Duroid RO6003 of relative dielectric constant 6.15 and loss tangent 0.013 at 35 GHz was used as the EMXT substrate. Gap "g," substrate thickness "h," and stripe width "w" determine the bandgap, or, resonant frequency F_{res} of the EMXT. The through substrate vias are included to suppress the undesirable surface modes [11]. In this work, the metal strips have a width of 14 mil and are separated by a gap of 6 mil. The substrate has a thickness of 25 mil and the substrate vias have a checker board distribution.

An EMXT surface can be characterized by the reflection measurement depicted in Fig. 2(a). The reflection coefficient of a waveguide terminated by the EMXT surface under test is measured; and from the measured reflection coefficient, F_{res}, the bandwidth and the loss of the EMXT can all be determined. Fig. 2(b) shows the measured reflection phase as a function of frequency for the EMXT used in this work. At the resonant frequency F_{res} of 35 GHz, the reflection phase is zero degrees. In

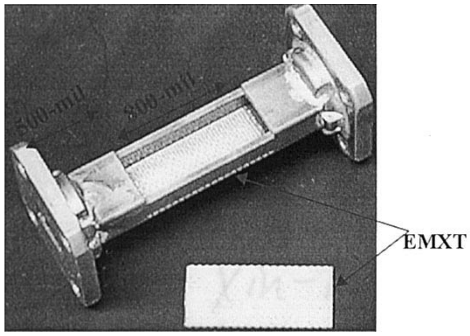


Fig. 3. Picture of the waveguide band-stop filter with its top and bottom walls replaced by striped-EMXT surfaces.

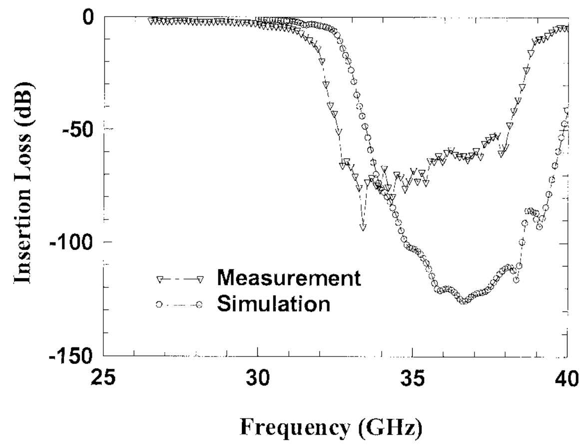


Fig. 4. Measured and HFSS simulated frequency response (26.5–40 GHz) of the waveguide band-stop filter with EMXT top and bottom walls. Notice the correlation between the stopband and the bandgap in Fig. 2.

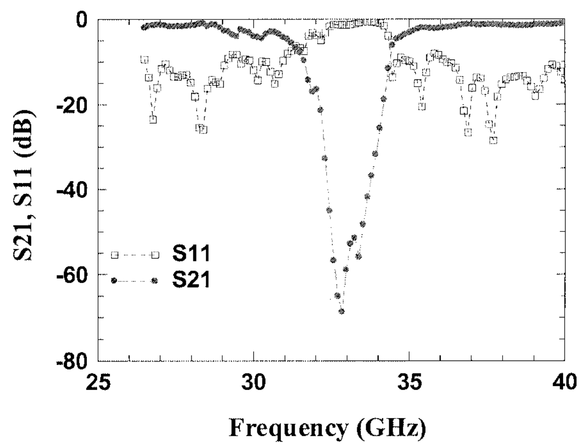


Fig. 5. Measured insertion loss and return loss of the EMXT band-stop filter with only one EMXT wall. Notice the change of the stopband center and the bandwidth comparing to the two-wall EMXT guide.

other words, 35 GHz is the center of the EMXT bandgap. The bandwidth (defined to be from −90 to 90 degrees) of the EMXT ranges from 31 GHz to about 40 GHz. The step in the reflection phase is due to undesirable substrate modes.

B. EMXT Waveguide Band-Stop Filter

In references [5], [10], the sidewalls of a rectangular waveguide are replaced by striped-EMXT surfaces oriented to inhibit transverse current in the waveguide walls and to achieve a TEM waveguide and a phase shifter. In this work, the top and bottom walls of a regular WR28 waveguide are replaced by striped-EMXT surfaces, with the strips oriented perpendicular to the wave travelling direction in the guide to inhibit longitudinal surface currents. Since no longitudinal rf current is allowed to flow along the EMXT surface within its bandgap, all modes are inhibited and an effective band-stop filter can be realized in this configuration. Fig. 3 shows a picture of the EMXT waveguide band-stop filter. The top and bottom walls of a WR28 waveguide were cut, and two 800-mil-long EMXT described above were flush mounted, with the striped surfaces facing inside of the waveguide. Thus, this filter is made of 800-mil long EMXT guide with 500-mil long metal guide extension at both the input and the output sides.

III. Results and Discussion

The EMXT waveguide filter response throughout the entire Ka-band (26.5–40 GHz) is measured by using a vector network analyzer. The EMXT waveguide has a stopband centered around 35 GHz and spanning from about 31 to 40 GHz, just as the reflection measurement of the EMXT would predict (see Fig. 2). As shown in Fig. 4, up to 80 dB of isolation (limited by the network analyzer sensitivity) is measured within the stopband. From 31.2 to 32.2 GHz, the measured isolation increases from 6 dB to 35 dB. Outside of the stopband, less than 2 dB of loss is measured, and it is mainly due to the dielectric loss of the substrate (confirmed by finite-element simulations described in the following section).

The three-dimensional (3-D) EM simulator Ansoft HFSS is used to simulate the frequency response of the above EMXT waveguide. Simulated and measured results are compared in Fig. 4. Agreement between simulation and measurement is quite good, except that the simulation predicts a stopband center around 37 GHz rather than the measured 35 GHz. This 5% discrepancy in frequency is probably due to manufacturing imperfections (i.e., some of the substrate vias are not centered perfectly in the metal strips) and uncertainty in the substrate dielectric constant.

A waveguide with only one wall replaced by the EMXT surface has also been investigated. Fig. 5 shows the measured return loss and insertion loss of the waveguide with only one EMXT wall. The center frequency of the stopband is lower and the bandwidth is narrower compared to the waveguide with two EMXT walls. The return loss is low (averaging lower than 1 dB) for the stopband. It is worth mentioning that a band select system could be constructed by using this EMXT waveguide and a circulator.

Agile band-stop filters could be realized by using tunable EMXT surfaces. InP quantum-barrier varactor loaded EMXT has been demonstrated to have a tunable resonant frequency covering almost the entire Ka-band with less than 10 V of bias voltage [11]. Fig. 6 shows the measured reflection phase of the InP varactor EMXT as a function of frequency at various bias voltages. The direct connection between the reflection characteristics of the EMXT surface and the band-stop behavior of the EMXT waveguide (Fig. 2 and Fig. 4) indicates that a tunable

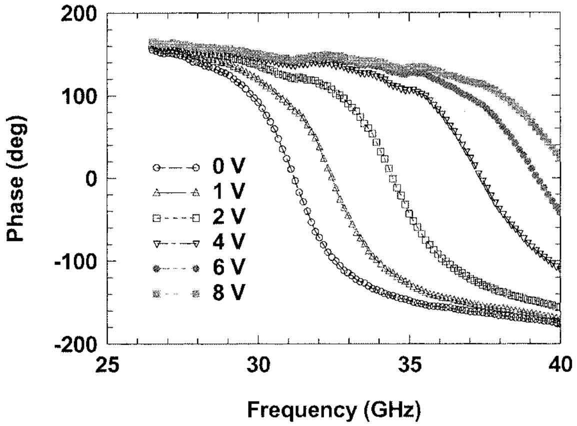


Fig. 6. Reflection phase results at various bias voltages of an InP quantum-barrier varactor based tunable EMXT. The resonant frequency is tuned from 31 to above 40 GHz.

band-stop waveguide filter could be achieved using the demonstrated tunable EMXT as the top and bottom walls. With the top and bottom EMXT walls individually controlled, both the center frequency and the bandwidth of the stopband could be potentially tuned in the order of nanoseconds (only limited by the biasing circuit). In addition, multiband rejection is also possible. It is worth noting that in contrast of the EMXT phase shifter described in reference [11], the loss associated with the series resistance of the tuning devices of the EMXT near its resonant frequency would not impact the performance of the band-stop filter. Instead, the resonant loss would enhance the band rejection of the filter.

IV. Conclusion

A waveguide band-stop filter using EMXT walls with a bandgap centered at 35 GHz has been demonstrated. The rejection band is a direct reflection of the EMXT bandgap so that the EMXT design determines the center frequency and the bandwidth of the filter. High isolation (>70 dB) for the stopband and low loss (<2 dB) outside of the stopband are measured. High performance frequency and bandwidth agile filters can be made using tunable EMXT walls.

References

[1] D. Sievenpiper, L. Zhang, and E. Yablonovitch, “High-impedance electromagnetic ground planes,” in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 1999, pp. 1529–1532.

[2] H. Xin, K. Matsugatani, M. Kim, J. B. Hacker, J. A. Higgins, M. Tanaka, and M. J. Rosker, “Mutual coupling reduction of low-profile monopole antennas on high impedance ground plane,” *Electron. Lett.*, vol. 38, Aug. 2002.

[3] M. Kim, J. B. Hacker, A. L. Sailer, S. Kim, D. Sievenpiper, and J. A. Higgins, “A rectangular TEM waveguide with photonic crystal walls for excitation of quasioptical amplifiers,” in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 1999, pp. 543–546.

[4] F. R. Yang, K. P. Ma, Y. Qian, and T. Itoh, “A novel TEM waveguide using uniplanar compact photonic-bandgap (UC-PBG) structure,” *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2092–2098, Nov. 1999.

[5] J. A. Higgins, M. Kim, J. B. Hacker, and D. Sievenpiper, “The application of photonic crystals to quasioptic amplifiers,” *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2139–2143, Nov. 1999.

[6] C. Kariazidou, H. F. Contopanagos, and N. G. Alexopoulos, “Monolithic waveguide filters using printed photonic-bandgap materials,” *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 297–307, Feb. 2001.

[7] S. T. Chew and T. Itoh, “PBG-excited split-mode resonator bandpass filter,” *IEEE Microwave Guided Wave Lett.*, vol. 11, pp. 364–366, Sept. 2001.

[8] C.-Y. Chang and W.-C. Hsu, “Photonic bandgap dielectric waveguide filter,” *IEEE Microwave Guided Wave Lett.*, vol. 12, pp. 137–139, Apr. 2002.

[9] D. Sievenpiper, J. Schaffner, B. Loo, G. Tangonan, R. Harold, J. Pikulski, and R. Garcia, “Electronic beam steering using a varactor-tuned impedance surface,” in *IEEE AP-S Int. Symp.*, vol. 1, June 2001, pp. 174–177.

[10] J. A. Higgins, H. Xin, and A. Sailer, “Characteristics of Ka-band waveguide using electromagnetic crystal sidewalls,” in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 2002, pp. 1071–1074.

[11] J. A. Higgins, H. Xin, A. Sailer, and M. J. Rosker, “Ka-band waveguide phase shifter using electromagnetic crystal sidewalls,” *IEEE Trans. Microwave Theory Tech.*, submitted for publication.

[12] J. B. West, H. Xin, J. C. Mather, J. P. Doane, H. Kazemi, and J. A. Higgins, “A two-dimensional millimeter wave phase scanned lens utilizing analog photonic bandgap waveguide phase shifters,” *Proc. Allerton Antenna Applicat.*, Sept. 2002.