LEAKY-WAVE ANTENNA AND BAND-REJECT FILTER FOR MILLIMETER-WAVE INTEGRATED CIRCUITS

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Abstract

Grating structures fabricated in inverted strip dielectric waveguide have for the first time been used as millimeter-wave leaky-wave antennas and band-reject filters. Experimental results agree reasonably well with theoretical predictions.

Introduction

Grating structures are commonly employed in optics as beam couplers[1] and as frequency-sensitive reflectors for distributed feedback lasers.[2] However, such gratings have not yet been widely used at millimeter wavelengths. Since dielectric waveguides in millimeter-wave integrated circuits (MMIC) are low-frequency replicas of optical waveguide, it is clear that many techniques could be transferred from the optical to the millimeter-wave domain.

This paper reports the first reduction to practice of a frequency-scannable leaky-wave antenna and a band-reject filter made of grating structures implemented in the inverted strip dielectric (IS) waveguide[3,4]. The antenna and filter are compatible with and naturally complement the directional couplers, oscillators, and phase shifters that have already been developed using dielectric waveguide fabrication techniques[3-7]. Grating structures can be easily and economically fabricated in the IS guide. The performance of the antenna and the filter made of gratings can be optimized in a relatively easy and flexible manner. Hence, the development of these devices is likely to contribute to realization of high overall performance of millimeter-wave systems with modest cost and effort.

Grating Structures in IS Waveguide

The IS waveguide has a number of useful features. It is of low loss, has a ground plane for convenience of mounting solid-state devices, and is easy to fabricate. Unlike many other dielectric waveguides, the major portion of the energy launched in the IS guide, shown in Fig. 1, travels in the planar guiding layer (ϵ_2) and is also transversely concentrated in the region immediately above the dielectric strip (ϵ_1). Many functional devices[4] can be created by appropriately arranging the location and length of one or more dielectric strips while leaving the guiding layer intact, although principal parts of wave interaction take place in the guiding layer.

Gratings can also be created by periodically modulating the geometrical or material nature of the dielectric strip and still leaving the guiding layer intact. For instance, as shown in Fig. 2, grooves are created periodically, in the dielectric strip. This groove configuration perturbes the transmission characteristics of the IS guide periodically, thereby functioning as a grating.

Leaky-Wave Antenna

Electromagnetic waves in a grating region can be represented in terms of space harmonics whose phase constants are:

$$\beta_m = \beta_o + \frac{2m\pi}{d} \qquad m = 0, \pm1, \pm2, \ldots \qquad (1)$$

where d is the grating period and β_o is the phase constant of the dominant (m = 0) space harmonic determined by the excitation of the grating. If perturbation due to each unit cell of the grating is small, β_o is very close to the phase constant β_{sw} of a surface wave in the unperturbed IS guide. When the period d is chosen such that the phase constant of the p^{th} harmonic (say, p = -1) satisfies:

$$|\beta_p/k| < 1 \text{ (k = free space wavenumber)} \qquad (2)$$

the grating supports a leaky wave and the energy traveling in the grating leaks into free space along the direction $\theta = \sin^{-1}(\beta_p/k)$ measured from the broadside of the grating[8]. For small perturbation the radiation pattern can be approximated by[8].

$$|f(\theta)|^2 = \frac{1}{N^2} \left| \frac{\sin (N\psi/2)}{\sin (\psi/2)} \right|^2 \qquad (3)$$

$$\psi = kd \sin \theta - \beta_o d$$

where N is the number of grating elements.

A leaky-wave IS guide antenna was designed for 60 GHz. After the design was completed, all the dimensions were scaled by the factor of four to permit experiments at 15 GHz. This scaling is for demonstrating the operating principle with modest cost and time for fabrication. A model antenna is pictured in Fig. 3. Since the guiding layer (Stycast Hik, ϵ_r = 3.75) is non-transparent for light, a disassembled view was taken. The smaller tip on one end of the guiding layer is the transition region for launching, whereas the larger one on the other end is to avoid the reflection of energy left unradiated at the grating.

Fig. 4 shows measured and computed [using (3)] radiation patterns of the model antenna. At 15 GHz, the main beam is directed -26° (26° toward the backward direction) from the broadside, while at 17 GHz the main beam direction is -10° from the broadside. Measured and computed sidelobe levels are -10 dB and -13 dB, respectively at both frequencies.

Band-Reject Filter

When d is chosen as:

$$\beta_o d = \pi \ , \ \beta_o \approx \beta_{sw} \quad (4)$$

the grating no longer radiates, but rather it exhibits a stopband phenomenon. The energy incident on the grating is reflected back at the frequency at which (4) is satisfied. Hence, the reflection phenomenon is frequency sensitive and such a grating can be used as a band-reject filter. The bandwidth and reflectance depend on the grating profile, the length of grating region, etc.

Because the present setup does not allow measurement of transmission characteristics of the band-reject filter, its reflection properties are measured instead. Fig. 5(a) shows the reflection from a 30-element grating filter. The sharp dip around 15.4 GHz corresponds to the stop band. The cross-sectional dimensions of the IS guide and the grating profile of the filter are identical to those for the antenna, except that d is much smaller in the filter case to satisfy (4).

Fig. 5(b) depicts the reflection from an IS waveguide with dimensions identical to those in Fig. 5(a) but without any grating. Fig. 5(b) serves as a reference for Fig. 5(a). In these figures, the magnitude of reflected signals is measured in the downward direction from the zero level indicated by white, horizontal straight sweeps. The loaded Q of the filter is found to be around 100. The return loss characteristic of the filter in the stop band is rather poor (4 dB). However, the filter performance could be improved by increasing the number of elements and by controlling the grating profile more accurately.

The reflection property of the filter was predicted by the use of a simple analytical model as follows: Each grooved and non-grooved section that makes up a cell of the grating was first represented by a transmission line whose characteristics can be described by the effective dielectric constants[3]. Then these individual transmission lines were cascaded as a periodic structure. The return loss calculated by this method was 2.6 dB, which is 1.4 dB higher than the measured return loss. The discrepancy is attributed to loss of energy due to radiation and attenuation in the physical model and to the use of an oversimplified theory as described above; however, the center frequency can be predicted to within 2% by the use of the dispersion (k - β) diagram of the IS guide.

Conclusion

We have demonstrated for the first time that grating structures can be used as antennas and filters for millimeter-wave integrated circuits. Leaky-wave antennas of the type demonstrated can be implemented in the dielectric millimeter IC and can be efficiently coupled with a transmitter or a receiver front end. They are planar and frequency-scannable, and do not require a radome.

Grating type filters of the kind demonstrated are suitable for a number of applications. For instance, by the use of their frequency-sensitive reflection properties, two of the gratings separated by an appropriate distance could be employed as a resonator. On the other hand, two band-reject filters combined with a 3-dB hybrid can result in a band-pass filter.

The experimental results agree reasonably well with the theoretical predictions. Therefore, it appears that accurate design procedures can be found without undue difficulty.

References

1. K. Ogawa, W.S.C. Chang, B. Sopori and F. J. Rosenbaum, "A theoretical analysis of etched grating couplers for integrated optics," IEEE J. Quan. Elect., Vol. QE-9, pp. 29-42, Jan. 1973.

2. S. Wang, "Principles of distributed feedback and distributed Bragg-reflection lasers," IEEE J. Quan. Elect., Vol QE-10, pp. 413-427, April 1974.

3. T. Itoh, "Inverted strip dielectric waveguide for millimeter-wave integrated circuits," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-24, pp. 821-827, Nov. 1976.

4. R. Rudokas and T. Itoh, "Passive millimeter-wave IC components made of inverted strip dielectric waveguides," IEEE Trans. Micorwave Theory and Techniques, Vol. MTT-24, Dec. 1976.

5. H. Jacobs and M. M. Chrepta, "Electronic phase shifter for millimeter-wave seimconductor dielectric integrated circuits," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-22, pp. 411-417, April 1974.

6. R. M. Knox and P. P. Toulois, "A V-band receiver using image line integrated circuits,: Proc. Nat. Elect. Conf., Vol. 27, pp. 489-492, Oct. 1974.

7. H. Jacobs, G. Novick, C. M. LoCascio and M. M. Chrepta, "Measurement of guided wavelength in rectangular dielectric waveguides," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-24, pp. 815-820, Nov. 1976.

8. R. E. Collin and F. J. Zucker, Antenna Theory, Vol. 2, Chpas. 19 and 20, McGraw-Hill, New York, N. Y. 1969.

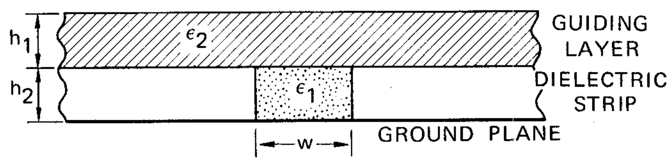


Fig. 1 Cross section of IS waveguide

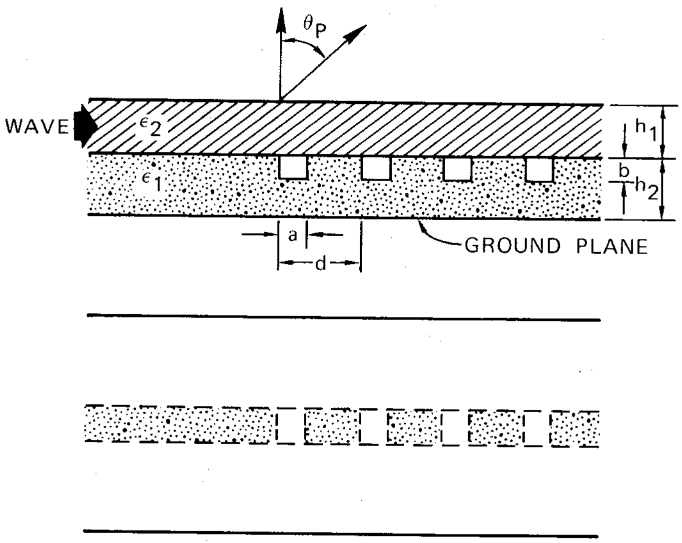


Fig. 2 Side and top views of grating configuration in IS waveguide

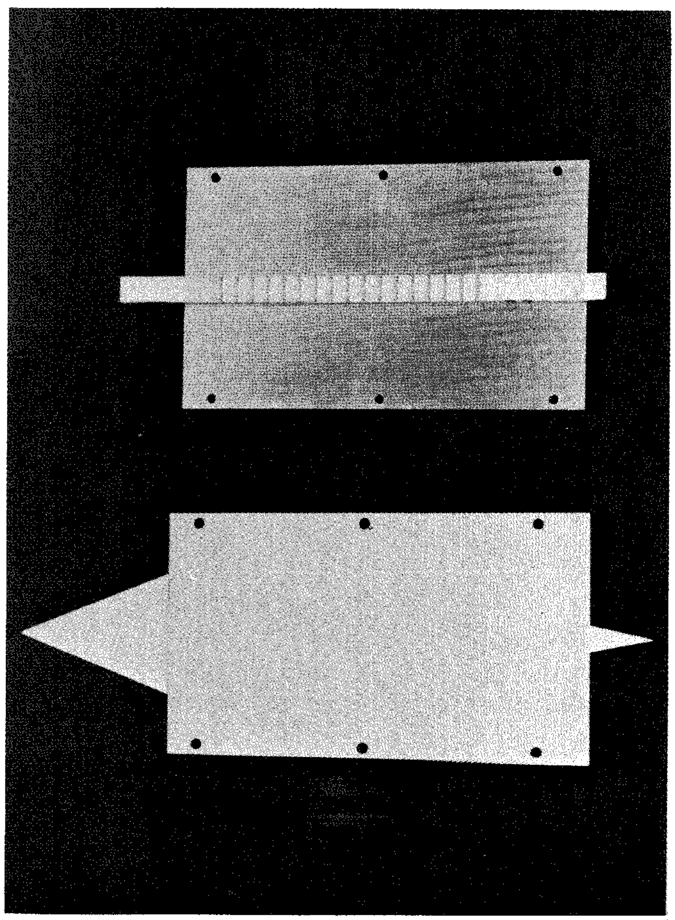


Fig. 3 Disassembled grating antenna

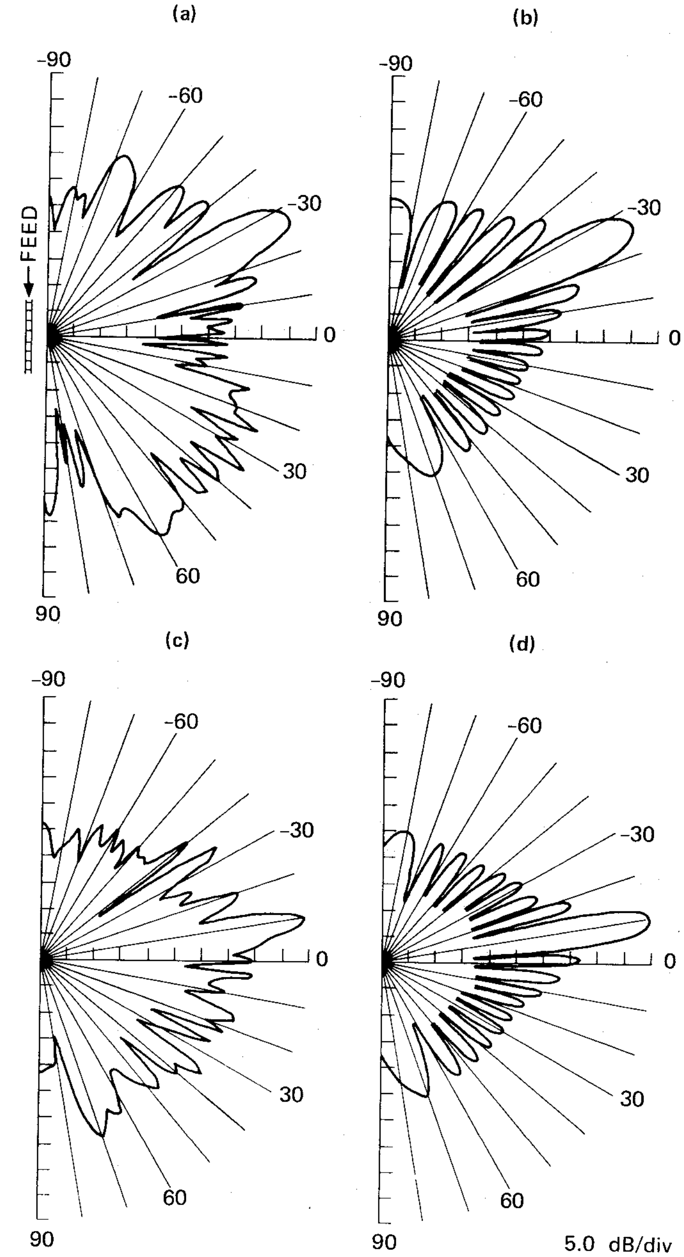
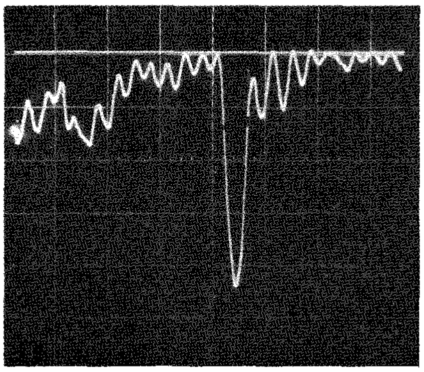
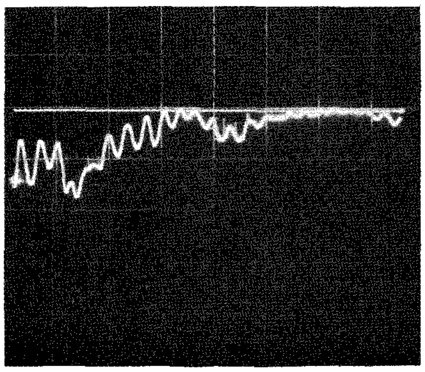


Fig. 4 Radiation patterns of grating antenna, d = 10.16 mm, a = 3.18 mm, b = 4.76 mm, $h_1 = h_2 = 6.35$ mm, $\epsilon_1 = 2.1$ (Teflon), $\epsilon_2 = 3.75$ (Stycast Hik), number of grating elements = 17. (a) Measured at 15 GHz. (b) Computed at 15 GHz. (c) Measured at 17 GHz. (d) Computed at 17 GHz.



20 mV/div
12.4–18 GHz

(a)



20 mV/div
12.4–18 GHz

(b)

Fig. 5 Reflection property of a grating filter. Parameters h_1, h_2, ϵ_1 and ϵ_2 are identical to Fig. 4. (a) Filter with d = 6.25 mm, a = 1.59 mm, b = 0.79 mm, number of grating elements = 30. (b) No grating for reference purposes.