A DISTRIBUTED FEEDBACK DIELECTRIC WAVEGUIDE OSCILLATOR WITH A BUILT-IN LEAKY-WAVE ANTENNA

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ABSTRACT

The high VSWR of a broadside-firing dielectric leaky-wave antenna is used for providing a feedback mechanism for the Gunn oscillator in a dielectric waveguide. The result is a Gunn oscillator with a built-in broadside antenna useful for dielectric microwave and millimeter wave integrated circuits.

Introduction

This paper describes the design principle and experimental results of a novel distributed Bragg reflection (DBR) Gunn oscillator with an integral leaky-wave antenna. The composite structure is made in a dielectric waveguide and is believed useful for dielectric millimeter and microwave integrated circuits. The leaky-wave antenna integrated in the present structure is broadside-firing. In conventional antenna applications, such a broadside condition is avoided due to its high-VSWR characteristics. However, in the present work this high-VSWR is intentionally made use of for providing a frequency dependent positive feedback to the gain device in the oscillator.

In most dielectric millimeter-wave integrated circuits, a solid-state oscillator is made of a Gunn or IMPATT diode implanted in a rectangular dielectric waveguide cavity.[1] In such a structure, the Fresnel reflection from the end surfaces of the resonator provides feedback to the active device and leads to oscillation. In the recently developed original version of DBR Gunn oscillators,[2] however, the feedback is provided by the so-called surface-wave stop-band phenomena of the grating structures created in the dielectric waveguide.[3] As is also demonstrated in the band-reject filter,[4] the surface wave is strongly reflected back from the grating structure in a narrow frequency region. Such a frequency sensitive reflection is useful for realizing a high Q cavity for the oscillator made of a dielectric waveguide. In the operating principle, the DBR oscillator resembles DBR GaAs lasers developed in optics.[5,6]

It is well known that the stop-band phenomena appear not only in the surface wave but also in the leaky-wave regions.[7] In the structure described in this paper, the leaky-wave stop-band as well as the surface-wave stop-band is used for providing positive feedback leading to oscillation. The oscillator created in a dielectric waveguide has a grating structure giving a surface-wave stop-band on one side of the gain device and another providing a leaky-wave stop-band on the other side. This leaky-wave structure also gives rise to the broadside radiation which facilitates easy output power extraction.

Oscillator Design

Before describing the new DBR oscillator with an integrated antenna, let us briefly review the configuration of the original version of DBR oscillators.[2] The original version of the DBR oscillator employing surface-wave stop-band can be implemented as in Fig. 1 by placing a Gunn diode in a small vertical hole drilled in a dielectric image guide.[2] The ground plane is used as a heat sink as well as a dc bias return for the diode. The bias is supplied by a thin wire connected to the positive terminal of the diode. Although various types of gratings can be used, mechanically created notch type periodic grooves have been used in the dielectric waveguide. For the surface-wave stop-band, the period of grating d is chosen such that

$$\beta d = \pi \tag{1}$$

where β is the phase constant of the dielectric waveguide without gratings. β can be approximated by the following dispersion relation[8]:

$$\cos\beta d = \cos(\beta_G a)\cos[\beta_{NG}(d-a)] - \tfrac{1}{2}(\beta_{NG}/\beta_G + \beta_G/\beta_{NG})\sin(\beta_G a)\sin[\beta_{NG}(d-a)] \tag{2}$$

where β_G and β_{NG} are the phase constants in the grooved and non-grooved sections of the waveguide. In the stop-band, β is complex due to mode coupling between forward and backward waves. When we neglect this mode coupling, the dispersion curve (kd-βd diagram) will look like as shown in Fig. 2. Point A ($\beta d = \pi$) corresponds to surface-wave stop-band where strong mode coupling occurs between two space harmonics β_0 and β_{-1} (negative β means travelling backward). All of these space harmonics are interrelated via

$$\beta_m = \beta_0 + \frac{2m\pi}{d}\ ;\ m = 0,\ 1,\ 2,\ \ldots \tag{3}$$

where β_0 is the phase constant of the dominant (m = 0) space harmonic.

The leaky-wave stop-band is created at $\beta d = 2\pi$ (Point B in Fig. 2) by the interaction between space harmonics β_0 and $-\beta_{-2}$ which are no longer surface waves, and the radiation peak is in the broadside direction normal to the waveguide surface. This leaky-wave stop-band gives strong reflection due to backward space harmonic $-\beta_{-2}$ coupled to β_0, which results in high VSWR.

The new DBR oscillator using the high VSWR leaky-wave stop-band is shown in Fig. 3. In this structure, the left-hand side of the Gunn diode provides a dual function. It provides the reflection for oscillation as well as the broadside radiation for the antenna. The period of grating on the left is two times that of the right-hand surface-wave structure, viz., $\beta d = 2\pi$ on the left-hand side and $\beta d = \pi$ on the right. The radiation from the leaky-wave structure can be determined by

$$\theta = \sin^{-1}\left(\frac{\beta_{-1}}{k}\right) \tag{4}$$

where θ is the angle measured from the normal-to-surface direction and k is the free space wavenumber. At the leaky-wave stop-band (Point B), $\beta d \approx 2\pi$ which means radiation angle $\theta \simeq 0$ (broadside). This angle varies slightly depending on the oscillation frequency.

The reflection phenomena due to stop-band is frequency sensitive, and the bandwidth and the reflection depend on the grating profile, the length of the grating region, etc. In this work, bandwidth has been made wide (1GHz) so that oscillation can be easily attained.

Results and Discussions

Although we can provide the design at much higher millimeter frequencies, we selected here the X band for design and demonstration. This is due to better availability of measurement equipments and greater ease of experimental procedures. After the feasibility of our new concepts is demonstrated, we can go to higher frequencies later.

The dielectric waveguides are made of Custom HiK (ϵ_r = 10). The number of grating elements can be determined by the required magnitude of feedback. Fig. 4 shows the surface-wave reflection coefficient of a five-element notch type grating on the dielectric waveguide. Groove depth and the grating period are adjusted so as to give 10 GHz center frequency and 1 GHz bandwidth. The computed reflection coefficient is found to be 0.95. When only two grating elements are used, the reflection coefficient at 10 GHz reduces to 0.63. The latter may be useful for the output port of the original DBR oscillator shown in Fig. 1 in which the far ends of each grating is tapered to avoid unwanted end reflections. Oscillation frequencies and powers have been observed by varying bias voltage of the Gunn diode in the DBR oscillator shown in Fig. 1. The results are plotted in Fig. 5.

In the new DBR oscillator with a built-in leaky-wave antenna, we fixed the bias voltage at 7 volts, and the resonant frequency was observed around 9.995 GHz. The broadside radiation was observed as in Fig. 6. Main peak has been around the broadside direction and the radiation in all the other directions has been below -15 dB.

It is conjectured that the split of the main lobe is caused by two factors. One is the poor spectral purity which is not an inherent phenomena of this type of oscillator, but is rather due to our intentional broad-band design of the cavity. The other is due to the strong mode coupling between forward and backward space harmonics in the leaky-wave region which have different radiation angles.

Conclusions

We have presented initial results for a new oscillator structure utilizing a high VSWR leaky-wave stop-band. The structure is believed to give versatility in designing millimeter-wave integrated circuits. Further works need to be carried out to obtain spectral purity and better frequency control. It is possible to design grating structures with a much narrower bandwidth for more stable oscillation. Mechanical perturbation may be incorporated for adjusting the diode impedance for possible tuning of frequency and/or power.

References

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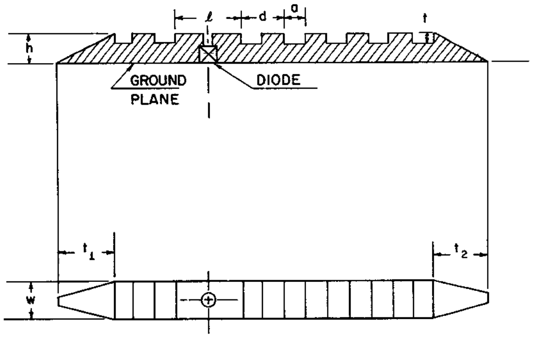

Fig. 1 An original version of the DBR oscillator structure; εr = 10, h = 3.0mm, ℓ = 16.5mm, d = 11.0mm, a = 5.5mm, w = 5.6mm, t = 0.9mm, t_1 = 16.0mm, t_2 = 11.5mm.

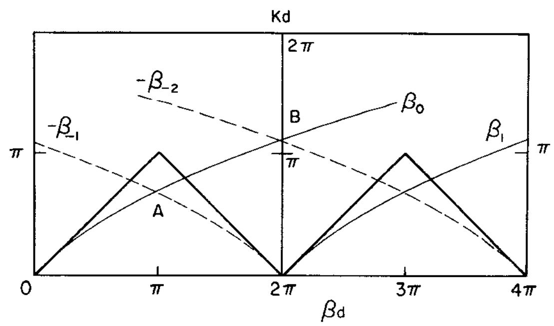

Fig.2 kd- βd diagram of the grating structure; εr = 10, w = 5.6mm, d = 11.0mm, a = 5.5mm, h = 3.0mm, t = 0.9mm.

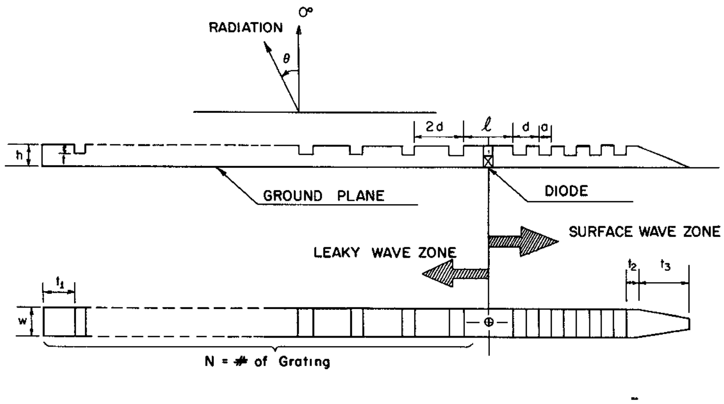

Fig. 3 Structure of a new DBR oscillator with a built-in leaky-wave antenna; N = 10, εr = 10, ℓ = 22.0mm, d = 11.0mm, a = 4.0mm, w = 6.0mm, t = 0.9mm, h = 3.0mm, t_1 = 12.0mm, t_2 = 4.0mm, t_3 = 19.0mm.

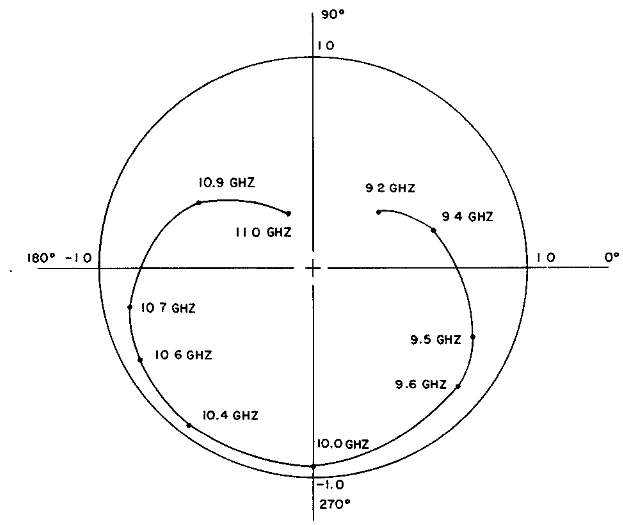

Fig. 4 Reflection coefficient of 5 element gratings in dielectric waveguide; Dimensions are the same as in Fig. 3.

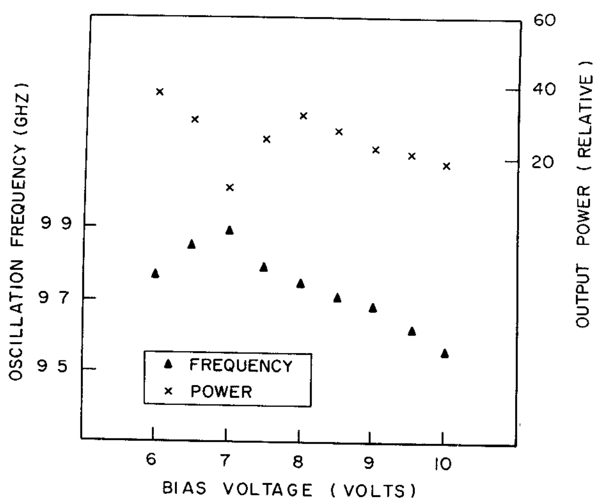

Fig. 5 Measured oscillation characteristics of the oscillator in Fig. 1.

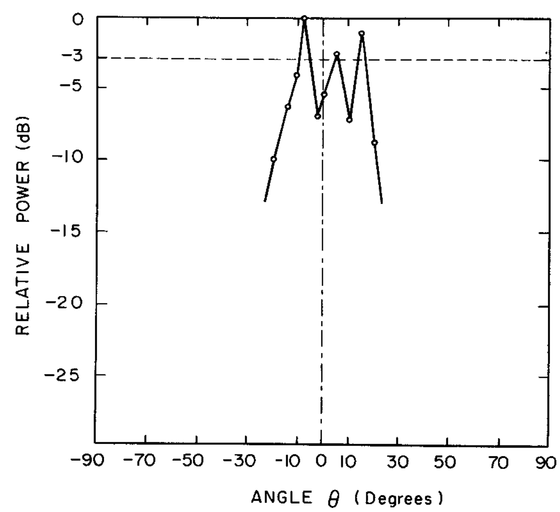

Fig. 6 Broadside radiation pattern from the DBR oscillator in Fig. 3.