where many chips are employed in a single package. The same technique, in principle, can be also applied to the higher frequency range.

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Distributed Bragg Reflector Gunn Oscillators for Dielectric Millimeter-Wave Integrated Circuits

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***Abstract*—A new Gunn oscillator is proposed for microwave and millimeter-wave integrated circuits. The device consists of a Gunn diode placed in a dielectric waveguide in which grating structures are created. The gratings provide frequency-selective feedback to the diode, enabling a stable oscillation. After the design principle is presented, observed oscillation characteristics of prototype oscillators are reported. Some problems as well as future directions for improvement are discussed. Potential applications as multiple-element high-power oscillators are also proposed.**

I. INTRODUCTION

THIS PAPER describes a new Gunn oscillator for dielectric waveguide-type microwave and millimeter-wave integrated circuits and reports some preliminary experimental results. Unlike conventional Gunn or IMPATT oscillators created in a rectangular dielectric cavity, the present structure makes use of the stopband phenomena of the grating structure as a mechanism to provide feedback to the diode. The principle of operation is quite similar to the distributed Bragg reflector (DBR) lasers used in integrated optical circuits. The new device may be potentially useful for developing a multiple-diode high-power oscillator. Before discussing the technical details, some background will be presented.

Dielectric waveguide structures [1]–[3] have been suggested as alternatives to printed-line type millimeter-wave integrated circuits [4], and a number of passive and active components have been created [5]–[7]. A typical solid-state oscillator for dielectric waveguide structures is made of a Gunn or IMPATT diode implemented in a rectangular dielectric waveguide cavity [6]. In such a structure, the oscillation frequency is determined by the cavity dimensions and the diode impedance. The oscillation frequency can be controlled somewhat by varying the bias voltage as well. One drawback of this type of oscillator is that, when the cavity gets longer, there may be more than one longitudinal resonance. Hence, if more than one diode is implanted for the purpose of increasing the output power, coherent oscillations may not be obtained because different diodes can couple with different modes. Another problem is related to fabrication. As the operating frequency gets higher, it becomes increasingly difficult to create a rectangular dielectric cavity in integrated circuits.

The new oscillator structure proposed in this paper may alleviate the problems described in the previous paragraph. The basic structure is shown in Fig. 1(a). A Gunn

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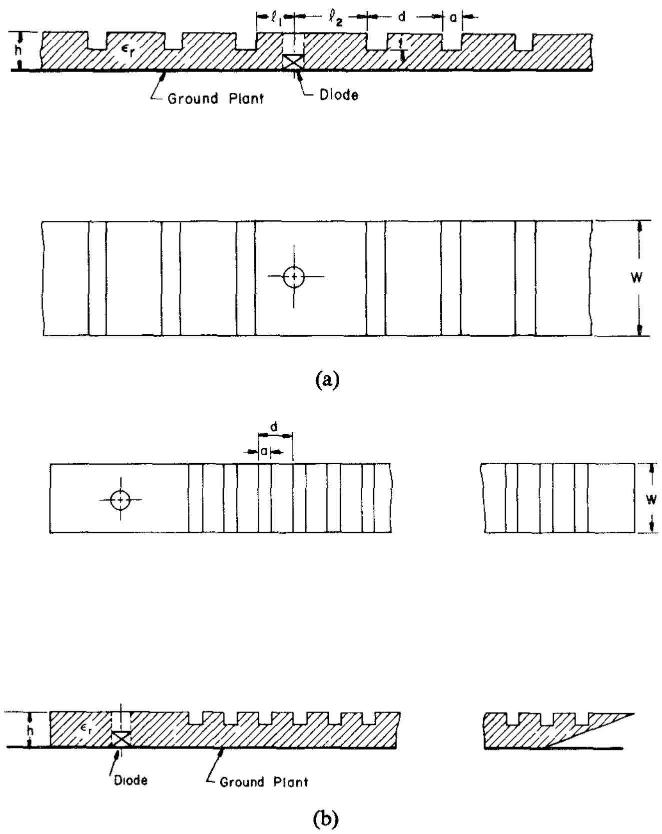

Fig. 1. Oscillator configurations. (a) DBR oscillator. (b) Semi-DBR oscillator.

diode is implanted in a small vertical hole drilled at the center in the cross section of a long dielectric guide. On both sides of the diode periodic gratings are created in the dielectric guide. It is well known that the periodic structure in the dielectric waveguide exhibits so-called stopband phenomena [8], [9]. Hence, looking into both directions along the waveguide axis from the diode, we obtain frequency-selective reflectors. The structure now becomes a diode implanted in a cavity which has a high Q only at frequencies in the stopband. It is expected that, if the diode impedance is chosen appropriately, the oscillation frequency is forced to fall in this stopband, because the cavity Q is quite low outside the stopband.

Grating structures have previously been used in integrated optical circuits to create DBR lasers [10], [11]. In DBR lasers, grating structures are created on both sides of the gain medium for positive feedback leading to oscillation. The distributed Bragg reflection is identical to the stopband phenomenon referred to above. It may, therefore, be appropriate to call the proposed structure in this paper a DBR Gunn oscillator.

The DBR oscillator has potentially several attractive features. First, as the operating frequency gets higher, creation of gratings can become economically more advantageous than that of rectangular cavities, because a planar technology may be applicable to an axially long top surface of the waveguide. Second, as the gratings exhibit high reflection properties only in the stopband region which can be made narrow, the DBR structures may eliminate potential multimoding problems in an oscillator in which several diodes are incorporated to increase the output power. For such multiple diode arrangements, these diodes must not be placed too close to each other due to heat dissipation requirements. This increases the length of the cavity l which is equal to the separation of two grating sections (DBR's). If two grating sections were replaced with frequency-independent reflectors, e.g., the end surfaces of conventional rectangular resonators, such a long cavity can support a number of axial modes, each separated by the frequency increment of $\Delta f = v/2l$, where v is the phase velocity of the guided wave, and l is the length of cavity between the reflectors. In the DBR oscillators, however, two grating sections are frequency-selective. Hence, it is possible to obtain a single-mode oscillation in which only one axial mode is selected by designing the center frequency of the stopband of the gratings to coincide with this mode, and making Q's of the resonator at all other modes sufficiently low. This is possible because the stopband can be made much narrower than the axial mode separation Δf so that these modes fall in the passband of the grating, and no reflection from the grating occurs.

The third feature is that the use of grating structures may relax the requirement of high dielectric material to be used for the cavity. In conventional oscillators with a rectangular cavity, it is preferable to use a material with a high dielectric constant to increase the Fresnel reflection from the end surfaces of the resonator. In the present setup, the reflection (or feedback) is provided by the distributed wave-interaction mechanism in the gratings. Large reflection coefficients can still be obtained by an appropriate design of gratings, even in the waveguide made of low-permittivity materials.

II. Oscillator Design

Fig. 1(a) shows the structure of DBR oscillators. A Gunn diode is placed in a small cylindrical hole in a dielectric image guide. Although IMPATT diodes may also be used, we employed Gunn diodes in this work. The ground plane is used as a heat sink as well as the dc bias return for the diode. The bias is supplied through a thin wire connected to the positive terminal of the diode. The gratings are of notch type, that is, periodic grooves are created mechanically on the top surface of the image guide. However, other types of gratings can also be used. At higher frequencies, photolithographic procedures may be more convenient and economical.

Fig. 1(b) is a semi-DBR oscillator in the sense that only one grating reflector is used, and the reflection from the other side comes from the end surface of the truncated image guide. We have planned to use this structure to obtain experience of controlling the oscillation by changing the cavity length.

The oscillation mechanism can be explained from the characteristics of the diode and gratings. We will first describe the nature of the latter. Detailed analyses on the characteristics of the grating structures in a dielectric

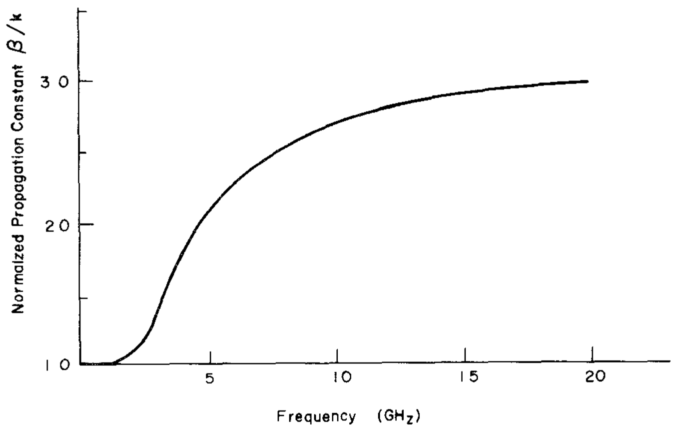

Fig. 2. Dispersion characteristics of an image guide without gratings; $\epsilon_r=10.0$, $w=6.35$ mm, $h=3.18$ mm.

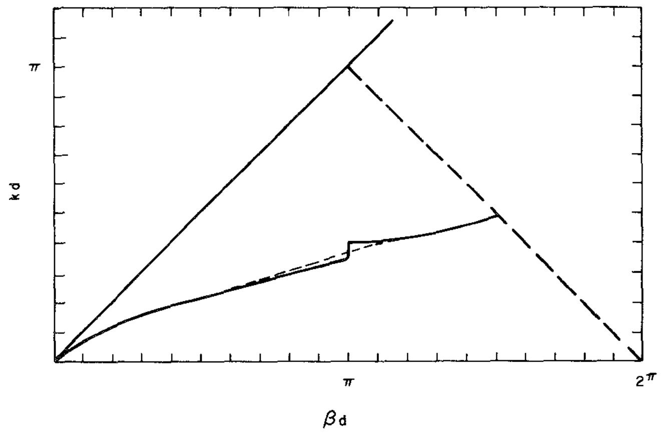

Fig. 3. $k-\beta$ diagram of a grating structure in an image guide; $\epsilon_r=10.0$, $w=6.35$ mm, $h=3.18$ mm.

waveguide have been reported [8], [9]. When the period of grating d is chosen, such that

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

where β is the propagation constant of unperturbed waveguide (without gratings), then the stopband appears at frequencies for which (1) holds. The width, center frequency, and Q of the stopband depend on the grating profile, such as the shape of the grooves, and their depth and width.

The starting point of analyzing and designing the grating sections is to compute the dispersion characteristics of an unperturbed dielectric waveguide. To this end, one can use simple formulas given by Marcatili [12], or the more accurate effective dielectric constant method [1], [3]. A typical dispersion curve is presented in Fig. 2 for the structure used in the present experiment. Next, the $k-\beta$ diagram for the waveguide with a periodic grating is computed either by way of the coupled-mode theory [8], [11] or the more accurate approach [9]. A typical $k-\beta$ diagram computed by the coupled-mode analysis is presented in Fig. 3. The stopband is the region for which (1) holds. Note that the approximate location of the stopband can be obtained from the $k-\beta$ diagram of the unperturbed waveguide (dotted curve in Fig. 3), as soon as the value of d is given. In fact, in the design process, d is approximately chosen from the $k-\beta$ diagram of the unperturbed guide such that the stopband is created at the desired frequency.

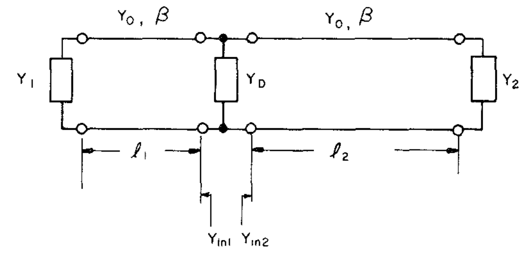

Fig. 4. Simplified equivalent circuit of a DBR oscillator.

In the stopband, the input impedance to a semi-infinite grating becomes reactive if there is no propagation loss in the waveguide. In practice, however, it has a small real part due partly to the propagation loss and partly to the load resistance. The latter appears in the input impedance because the actual grating has a finite length, and a certain amount of incident power is transmitted through the grating. Considering these arguments, we may derive a simplified equivalent circuit in Fig. 4 for the DBR oscillator. From this equivalent circuit, the oscillation condition is readily obtained:

$$Y_{\text{in}1}+Y_D+Y_{\text{in}2}=0 \tag{2}$$

$$Y_{\text{in}1}=\frac{Y_1+jY_0\tan\beta l_1}{Y_0+jY_1\tan\beta l_1} \tag{3}$$

$$Y_{\text{in}2}=\frac{Y_2+jY_0\tan\beta l_2}{Y_0+jY_2\tan\beta l_2} \tag{4}$$

where we neglected the propagation losses in the waveguides between the diode and two gratings. Also, Y_1 and Y_2 are input admittances at the entrances of gratings, and they are almost imaginary (reactive) in the stopband and almost real outside the stopband. Equation (2) can also be applied to the semi-DBR oscillator, provided Y_1 is replaced with the admittance corresponding to the truncated end surface of the waveguide.

The exact form of diode admittance is not known. It depends on the mounting structure, bias line impedance, etc. Compared with the diode mounted in a closed metal waveguide [13], the analysis to obtain the diode admittance is more involved, because radiation modes as well as discrete modes must be taken into account in an open structure such as the image guide. Such an analysis will not be reported here. Rather, in the present work, the diode admittance was adjusted to obtain oscillation by means of a loading to the diode, adjustment of the location of the diode, etc.

To increase the spectral purity of the oscillator output, the stopband of the gratings needs to be narrow. However, in such a case, it may be difficult to attain the oscillation condition, because (2) must be satisfied in the narrow stopband region. Once the cavity is made, it is difficult to adjust Y_{in1} and Y_{in2}, and only Y_D may be adjustable. For this reason, in the present work where attaining the oscillation is more important than the spectral purity, we tried to design the stopband of the gratings relatively wide. This can be done by making the grooves of grating sections rather deep. In gratings with deeper grooves, the wave interaction becomes stronger, resulting in a wider stopband.

III. Experimental Results and Discussions

Experiments have been performed in the *Ku*-band by using image guides made of a dielectric material with the relative dielectric constant of $\epsilon_r = 10$. Dimensions of the image guide are given in Fig. 2. Several Gunn diodes supplied by different manufacturers have been used. Two or three values of the grating period d have been tested for both DBR (Fig. 1(a)) and semi-DBR (Fig. 1(b)) structures. Fig. 5 shows the grating cavities of typical DBR and semi-DBR oscillators. The far end of each grating section is tapered to avoid the unwanted reflection.

In the experiment, we first placed a diode in a hole created in waveguide structures identical to those shown in Fig. 5, but without gratings. We confirmed that in such structures no oscillation occurs. Next, we created one groove at a time and repeated the oscillation test. The number of grooves was increased until the oscillation occurred. It was found experimentally that, for the present waveguide dimensions and a particular Gunn diode used, at least five grooves are needed on one side of the diode in semi-DBR oscillators, and about the same number of grooves on both sides in DBR structures.

Figs. 6 and 7 show the oscillation frequency and power versus the diode bias voltage for DBR and semi-DBR oscillators. The output power from one end of the oscillator cavity was coupled to an open-ended *Ku*-band waveguide which was in turn connected to a frequency meter and a detector diode. Since no power meter was available, we only recorded the relative strength of the output of the detector as a measure of the oscillation power. The power cannot be directly compared between Figs. 6 and 7, because the amount of power radiated into one direction may not be the same in the DBR and semi-DBR configurations.

In the particular DBR oscillator for Fig. 6, $l_1 = l_2 \approx \lambda_g/4$ was chosen, where λ_g is the guide wavelength in the unperturbed waveguide. A number of different values have been used for l_1 and l_2 in the semi-DBR arrangement. It is seen that the oscillation frequency of this DBR oscillator is relatively insensitive to the bias whenever it oscillates. However, the oscillation takes place only in a relatively narrow bias range. This situation was also observed by using different diodes. The oscillation frequency changes in a wider range in most semi-DBR structures tested as shown in Fig. 7. Also, the range of the bias voltage for oscillation was wider than in typical DBR cases. One of the reasons for these phenomena may be due to the fact that l_1 and l_2 in all semi-DBR oscillators were longer than those in DBR structures. These results indicate DBR structures may be preferable for most applications requiring stable operations.

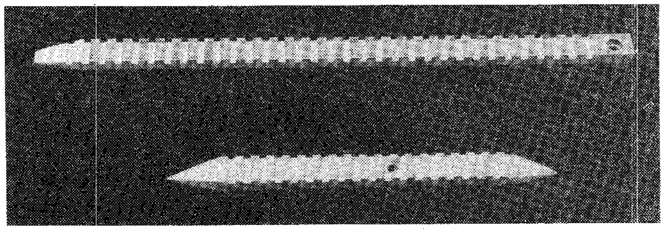

Fig. 5. DBR and semi-DBR oscillator cavities (removed from a ground plane for picture-taking purposes).

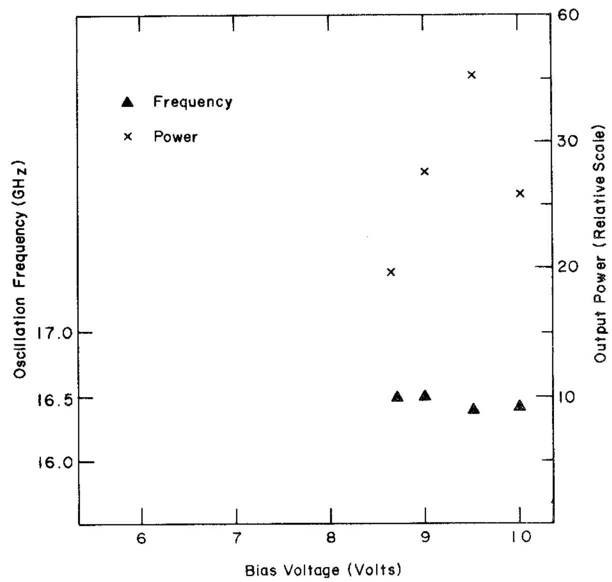

Fig. 6. Measured oscillation characteristics of a DBR oscillator; $\epsilon_r = 10.0$, $w = 6.35$ mm, $h = 3.18$ mm, $d = 3.25$ mm, $a = 1.58$ mm, $t = 0.79$ mm.

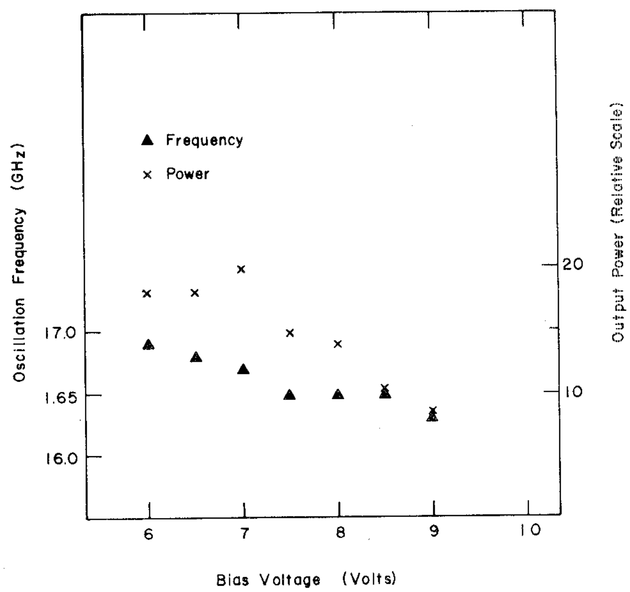

Fig. 7. Measured oscillation characteristics of a semi-DBR oscillator; $\epsilon_r = 10.0$, $w = 6.35$ mm, $h = 3.18$ mm, $d = 3.56$ mm, $a = 1.58$ mm, $t = 1.19$ mm.

IV. Conclusions

We have in this paper presented some initial results for proposed new oscillator structures with grating reflectors. The structures are expected to be useful for dielectric millimeter-wave integrated circuits. The work presented here is in no way complete. Some of the works to be carried out in the future may be summarized. First, better understanding of diode impedance in a dielectric waveguide is needed. Such a knowledge will be very useful for the design of oscillators. Second, if it were possible to incorporate electronic phase shifter [2] in the grating section, it would be possible to tune the oscillation frequency of the device electronically. This is because in such a grating the propagation constant β can be controlled by the phase shifter, and hence the stopband of the grating can be shifted [14]. Third, in the future, studies on DBR oscillators with several diodes should be contemplated. Such an oscillator, if successful, will emit a high power with good coherence. A more futuristic idea is to implement diode mechanism or gain medium directly in the waveguide.

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