Millimeter-Wave (*W*-Band) Quartz Image Guide Gunn Oscillator

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***Abstract*—Dielectric image-guide Gunn oscillator using fused quartz as the guide material has been investigated at frequencies around 94 GHz. Computer-controlled CO_2 laser cutting of quartz to the designed image-guide patterns has also been achieved. A resonant disk and pin bias circuit was used to tune the oscillator to an output power of 5 mW at the oscillation frequency of 94.2 GHz. An electronic frequency tuning of 350 MHz was measured with the oscillation characteristics similar to waveguide cavity oscillators. By varying the bias circuit disk and pin parameters, the Gunn-oscillator tuning characteristics have also been recorded for the future circuit performance optimization.**

I. Introduction

Dielectric GUIDING structures for the single-mode propagation of millimeter waves and submillimeter waves are of increasing theoretical and experimental interest [1]–[16]. Their low propagation loss and open guiding structures without metal enclosure offer certain distinct advantages for functional circuit integration over other circuit structures at extremely high frequencies. The open guiding structures, however, do allow radiation loss to occur when higher order modes are generated at physical discontinuities in the guide or when a sharp bend exists. By proper shielding with metallization on the guide surfaces, the radiation loss can be minimized. The advantage of the open guiding structure without metallized shielding was clearly demonstrated with the development of couplers and coupler-related circuits [15], [16]. Passive components integration in the dielectric image guide, involving solid-state devices and ferrite material, to form single-ended and balanced mixers, detectors, and ferrite circulators have also been demonstrated when proper metallization was applied for shielding and impedance matching [17]–[20].

For active solid-state device integration, image-guide configuration has been reasonably successful to integrate IMPATT and Gunn devices in semi-insulating silicon and boron nitride to form oscillators [18]–[21]. There, metallization is required either to form the resonance structure or to provide shielding and higher order mode suppression.

Two factors are of importance regarding dielectric wave-guiding structures for the fabrication of integrated circuits: material and circuit fabrication technique. The material used must have low-loss tangent. Its dielectric constant and circuit dimensions should not change significantly over the operating temperature range. Furthermore, the material property should be uniform without density variation and voids. The material should also be able to meet the environmental requirement for practical applications. Fabrication technique of the integrated circuit using the dielectric material depends on the material. At the present, dielectric circuit fabrication techniques include casting, multilayer thick-film silk-screening followed by high temperature hardening, cutting of soft green tape into circuit patterns followed by very high temperature hardening to form a ceramic guide circuit, and sandblasting through photo-etched metal mask. None of the above techniques appear to be satisfactory for producing a dielectric circuit of precisely defined dimensions. The sandblasting technique applies only to soft but not gummy material such as hot-pressed boron nitride. It is marginal for materials such as glass, quartz, and semiconductors. Ceramics are too hard for sandblasting. The thick-film silk screening is limited by the paste material available for low-loss propagation and the difficulty to build up thick layers with well-defined dimensions. The green tape technique has to face the problem of shrinkage during hardening. And the casting has to cope with the material uniformity and the expense of fabricating molds by machining.

This paper reports the fabrication of fused-quartz image-guide circuits using pulsed CO_2 laser for cutting the circuit patterns. Specifically, the test results of a 94-GHz quartz image-guide Gunn oscillator and the oscillator performance characteristics when the circuit parameters are varied, will be presented.

In a parallel effort, we are also working on the development of GaAs monolithic image-guide Gunn oscillator and Schottky junction mixer in a semi-insulating GaAs image-guide circuit. The Gunn and Schottky junction devices are being grown on semi-insulting GaAs substrate using molecular beam epitaxial and metal organic chemical vapor deposition techniques. The quartz image-guide oscillator circuit provides circuit parameters to be realized in the monolithic integrated circuit.

II. Fused-Quartz and Image-Guide Fabrication

Fused quartz and fused silica are being used by us to form dielectric image-guide circuits such as the balanced mixer and Gunn oscillator at frequencies of 94, 140, and 220 GHz. Both materials are made of 99.7-percent SiO_2. Fused quartz is manufactured by high temperature fusing

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of quartz crystals, and fused silica is a synthetic amorphous material made by flame hydrolysis. Both materials are hard and resistant to abrasion. Their low thermal expansion coefficient and high temperature characteristics allow them to withstand heat and thermal shock. With a dielectric constant of about 3.8 and a loss tangent of about 10^{-4} over a large frequency and temperature range, the materials are ideal for extremely high frequency applications. The materials can be easily metallized and plated with sufficient metal for soldering directly to a metal substrate to form the image guide. This image-guide structure is expected to be rugged because of the light mass and hardness of the quartz, and the good soldering bond between the quartz and the image-plane substrate.

Image-guide circuit fabrication was done by using pulsed CO_2 laser for cutting the quartz (or silica). A 2-in × 2-in quartz plate was placed on a movable platform with its $X-Y$ movement controlled by computer. The laser operates at 400-W averaged output power at a duty cycle of 20 percent. The optics provide an accuracy of 0.001 in and a repeatability of 0.0005 in. Fig. 1 shows the fused-quartz image-guide circuits fabricated with laser. The straight piece with a hole is for the 94-GHz Gunn oscillator. The center piece is a 3-dB hybrid coupler for a 94-GHz Gunn oscillator. The center piece is a 3-dB hybrid coupler for a 94-GHz balanced mixer. Notice that the coupler is made of one piece of quartz with a small slot halfway cut between the two dielectric guides at the coupling section. The slot of 0.020 in deep in a guide height of 0.048 in is used to make sure the propagation of even and odd modes for proper coupling. One-half of the coupler made with the slot cut through is also shown in the figure to show the repeatability of laser-cut patterns.

The pieces cut with the laser show well-defined straight and curved surfaces, sharp tapered ends, and a smooth hole. After the laser cutting, a very thin and porous quartz layer was formed on the surface, causing the surface to lose transparency. Metallization with Ni–Au on the porous surface has shown weak adhesion. A quick etch of the pieces in hydrogen fluoride (HF) immediately after the laser cutting was able to remove the porous layer and regain surface transparency. In certain laser cut pieces, stress in the quartz was also generated because of the intensive local heating. However, annealing at a temperature around 1000°C can eliminate the stress induced.

Fig. 2 plots the calculated results based on equations in [4] and [22] for a quartz image guide of aspect ratio (half the width over the height) equal one. The top figure plots the propagation characteristics, $\lambda_0/\lambda g$, as a function of the normalized guide height

$$B\left(=4b\sqrt{\epsilon_r-1}/\lambda_0\right)$$

for the fundamental E_{11}^Y mode and the next higher order E_{21}^Y mode. Here λ_0 is the free-space propagation wavelength and λg is the propagation wavelength in the image guide. The dimension b is the guide height, and $\epsilon_r (= 3.80)$ is the quartz relative dielectric constant. The middle figure plots the dielectric loss per wavelength of the image guide using a loss tangent of 10^{-3}. The bottom figure plots the image-guide conduction loss per wavelength using copper for the image plane. The ideal single-mode selection would require the reduced height B to be 1.4 which means an image-guide height of about 0.027 in. At B equal to 1.4 or less, the higher order E_{21}^Y mode cannot propagate.

Our selection of guide height equals 0.048 in, or $B = 2.54$, is based on the consideration of providing a resonance disk and pin bias circuit to a Gunn diode of height equal to 0.018 in in the quartz guide. Although this selection of a slightly oversized guide allows the E_{21}^Y mode to propagate, the E_{21}^Y mode will not be able to propagate through the image-guide-to-waveguide transition. Our experimental re-

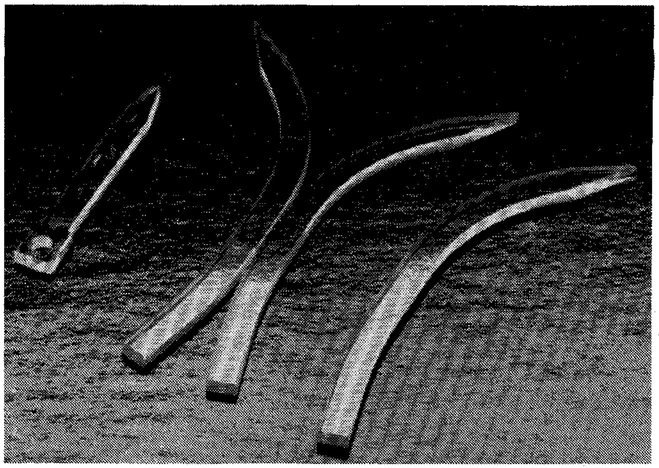


Fig. 1. Fused-quartz image guides fabricated by computer-controlled laser cutting.

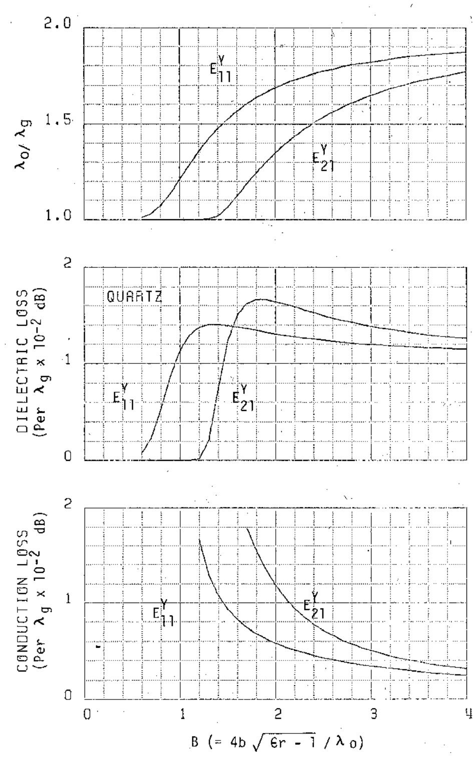


Fig. 2. Calculated propagation characteristics, conduction loss, and dielectric loss for a quartz image guide. Here λ_0 is the free-space wavelength, λ_g is the wavelength in quartz guide, b is the guide height, and ϵr is the relative dielectric constant of quartz.

sults on the quartz image-guide Gunn-oscillator performance further indicate that radiation along the image guide was negligible, which may mean that the E_{21}^{Y} mode was not actually excited at the Gunn-diode mount.

III. Quartz Image-Guide Gunn-Oscillator Circuit

The image-guide oscillator was constructed by integrating a packaged Gunn diode in the quartz guide. Device integration in image guide has been done in earlier work using several different configurations. One configuration placed a packaged IMPATT diode in a small hole drilled into a semi-insulating silicon image guide near one end of the guide. Ni–Au metallization on the silicon wafer was photo-etched to form a ring-shaped pattern on the top surface of the silicon. After the diode was soldered to the image plane and placed in the hole, gold ribbons were bonded to the top of the diode and connected to the ring-shaped metallization. A thin metal line, extending from the ring to either the end or one side of the image guide on the guide surface, was also photo-etched to form the constant current bias to the IMPATT diode. The metallized ring and the ribbons form a low-Q resonance circuit to the IMPATT diode. Radiation loss around this diode mount structure was observed since many modes were usually generated at the diode mount and this structure cannot suppress radiation. However, under certain tuning conditions, the radiation loss can be minimizable. Output power of 120 mW at 51.6 GHz and 50 mW at 58 GHz were obtained with single-drift IMPATT diode [18].

Another configuration was to enlarge the size of the hole for the diode package in the dielectric guide. Eventually, a rectangular cavity was formed in the dielectric. Metallization was then applied so that the sides of the cavity were covered with metal. A thin metal plate was used to cover the top of the cavity so that the structure resembles a conventional metal waveguide cavity, with a dielectric image guide inserted in the cavity from one side. For the IMPATT oscillator, current bias to the diode was done by soldering to the top of the diode a small wire which was extended outside of the cavity through a small opening in the cavity back or side wall. A gold ribbon was then bonded to the diode top. The ribbon extended forward from the diode to the top surface of the image guide for providing resonance inductance for oscillation. The shape and position of the ribbon was found critical to the oscillator power and frequency tuning. Using hot-pressed boron nitride as the dielectric material, the oscillators achieved output power of 240 mW at 64 GHz, and 93 mW at 91 GHz using double-drift IMPATT diodes [19]. For the Gunn oscillator, the structure is identical to the IMPATT oscillator design, except that a small metal disk soldered to the top of the diode was required. The disk and the gold ribbon formed the LC resonance circuit for the Gunn to oscillate. Again using hot-pressed boron nitride as the guide material, the oscillators achieved output power of 16 mW at 70 GHz. [19]. A third configuration for device integration was also applied for the Gunn oscillator. A

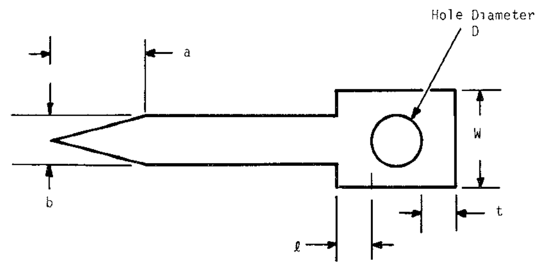


Fig. 3. Quartz image-guide dimensions for the W-band Gunn oscillator.

hot-pressed boron nitride image guide with a small hole for the diode in the guide, metallized at the bottom surface, and soldered to an image plane, was further metallized on all surfaces of the guide. Metallization was then selectively removed except the part on the surface around the hole. This way the cavity was shielded and the surfaces were at electrical ground with the image plane. To cover the hole, a large metal disk, with a pin and a small disk attached to its center, was soldered to image-guide top surface. The pin and the small disk, inserted into the hole, formed a LC resonance circuit. The diode was first threaded into a copper diode holder which in turn was inserted into an anodized aluminum cylinder. This cylinder was placed in a hole in the image-plane metal substrate directly underneath the hole in the dielectric. When the diode touched the small metal disk in the image-guide hole, negative bias voltage was applied to the diode holder to generate oscillation. The oscillators achieved output power of 3.2 mW at 92.8 GHz, 3.5 mW at 90.4 GHz, and 63 mW at 48 GHz [20].

The drawback with the second configuration with a large rectangular cavity was the gold ribbon which caused mechanical instability or microphonic oscillation. The drawback with the third configuration was the diode heat dissipation which was restricted by the anodized aluminum cylinder. The negative voltage bias to the diode was also not desirable in system applications.

In our present work, these drawbacks have been corrected. Fig. 3 shows the quartz image-guide dimensions for a W-band Gunn oscillator. The width W of the rectangular area equal to 0.120 in, which is larger than the guide width b of 0.095 in. This allows a large hole diameter D to be used. The large diameter D allows us to use a large bias disk for the Gunn-diode bias circuit. At the present, three sizes of hole diameter have been fabricated using laser cutting, for the purpose of circuit parameter variation. The guide width b is chosen for insertion into a W-band waveguide (0.100-in in width and 0.050-in in height). The tapered tip of the quartz, after insertion in the waveguide, forms an image-guide-to-waveguide transition with low transition loss. The quartz guide has a thickness of 0.048 in so that the aspect ratio of the guide is equal to 1. Since the packaged Gunn diode has a height of 0.018 in, the quartz

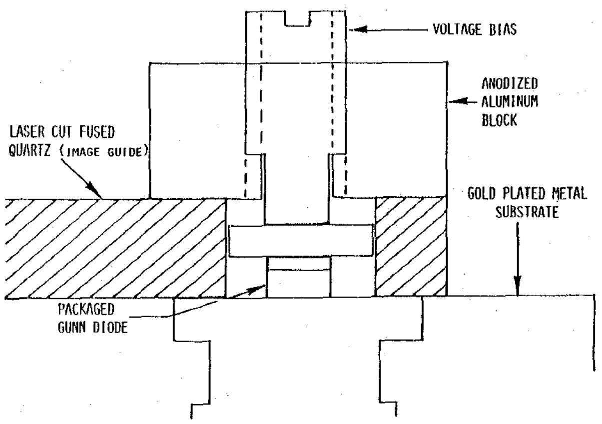


Fig. 4. Cross-sectional view of the quartz image-guide Gunn-oscillator diode mount area.

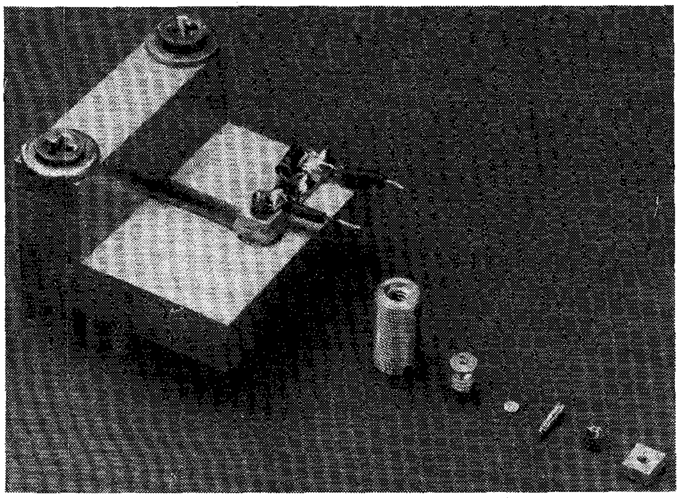


Fig. 5. Photograph of a *W*-band quartz image-guide Gunn oscillator.

guide height permits the use of the disk and pin resonance circuit of various thickness and length, respectively, for circuit optimization.

Metallization was applied to the surfaces at the rectangular region of the quartz indicated in Fig. 3. Metallization was done by sputtering 0.02-μm Inconel followed by 0.4-μm Au onto the quartz surfaces. The bottom surface of the quartz guide was also metallized and silver-epoxied to a gold-plated metal substrate as the image plane. The Gunn diode mount region is shown in Fig. 4. To facilitate diode replacement, a packaged Gunn diode was first threaded into a diode holder made of oxygen-free high conductivity copper. This diode holder was then threaded into the image-plane metal substrate. Diode thermal dissipation through the diode holder and metal substrate was found to be adequate. After the diode was inserted in the hole in the quartz guide, a metal disk was dropped in the hole to contact the diode. A small anodized aluminum block with a threaded hole was silver-epoxied to the top surface metallization of the quartz guide, and concentrically aligned with the hole in the quartz. A metal bias pin was then threaded through the anodized aluminum block for providing pressure contact to the metal disk and the diode. The thin oxide on the surface of the anodized aluminum block represents a large capacitance that can effectively block the millimeter wave from radiation at the bias circuit. Since the metal disk and pin form the *LC* resonance circuit, and the cavity is sealed with surface metallization, the circuit resembles a conventional waveguide Gunn oscillator circuit, however, with the advantage of compactness and ruggedness over the latter. Fig. 5 is a photograph of a completed *W*-band quartz image-guide Gunn oscillator. The parts for the diode mount including the diode bias circuit are also shown. Ruggedness of the circuit can be further improved by soldering the bias disk and pin directly to the diode.

IV. Experimental Results

The quartz Gunn oscillator was tested for output power and frequency when the diode was biased with a regulated voltage power supply. Fig. 6 shows one set of oscillation results measured. With proper combination of the bias pin dimensions (length and diameter) and the bias disk dimensions (diameter and thickness), oscillation around 94 GHz was obtained. The oscillator output power peaked at 5 mW (7 dBm) at 94.2 GHz as the bias voltage was varied. The output power measured included the loss in the image-guide-to-waveguide transition. This transition loss, however, is considered negligible. A frequency tuning range of 350 MHz with bias voltage was obtained. The power–frequency characteristics of the quartz Gunn oscillator are similar to those of the waveguide-cavity Gunn oscillator.

We have also started investigation of the various circuit parameters in order to optimize the oscillator performance. Our first step is to vary the bias pin and disk dimensions. Since we expect the pin and the disk to form the *LC* resonance circuit, the oscillation frequency should vary when the pin and disk parameters are varied. Fig. 7 shows that as we increase the pin diameter, the oscillation frequency increases as if the resonance inductance was lowered. Furthermore, the shorter the length of the pin, the less inductance the pin represents. This implies an increase in oscillation frequency. These are constant with any bias disk used. Fig. 8 shows the effect of varying the bias disk thickness and diameter on the oscillation frequency. As the disk thickness increases, the circuit becomes more capacitive at constant disk diameter. The oscillation frequency is lowered. Similarly, when the disk diameter increases, at constant disk thickness, the circuit is also more capacitive to cause lowering of oscillation frequency. To optimize the output power of the oscillator, we have also started investigation of the effect by varying the back short distance t, and the location of the hole l, indicated in Fig. 3. Furthermore, the width W, indicated in Fig. 3, will also be varied to determine its effect on the oscillation frequency and power.

Tests have also been conducted to investigate any power leakage along the top and side surfaces of the quartz image guide, at the Gunn diode mount region, and at the entrances of image guide into the waveguide. A horn followed by a detector were used as the probe, and no power was detected at these places. Placing a small metal block near

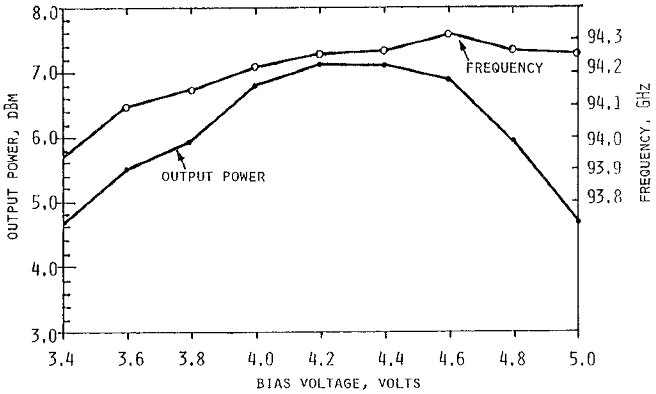


Fig. 6. 94-GHz quartz image-guide Gunn-oscillator test results.

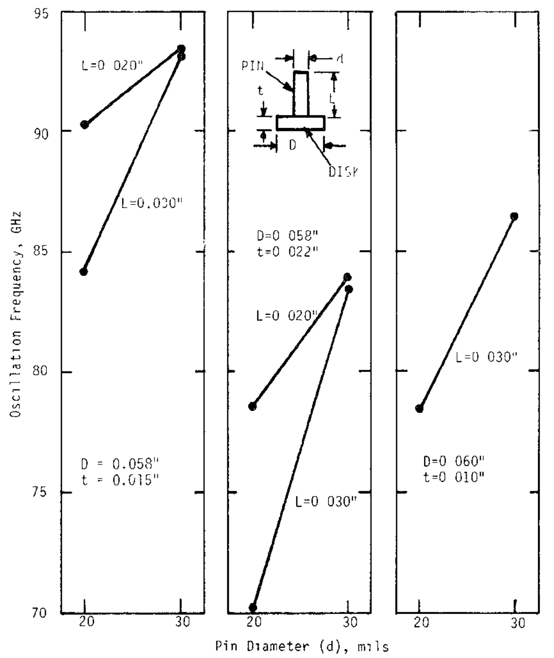
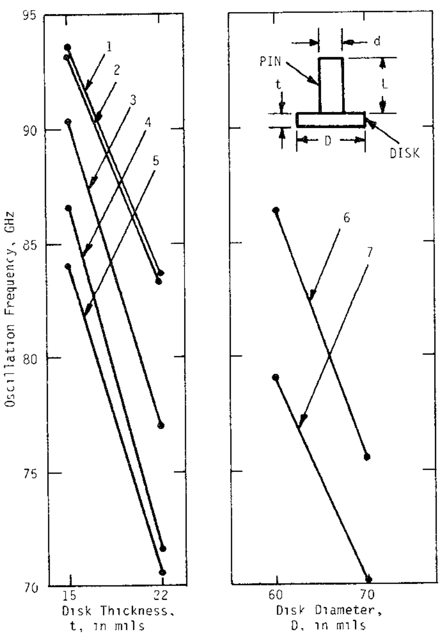


Fig. 7. *W*-band quartz image-guide Gunn-oscillator frequency as a function of the bias pin diameter.



	D	t	L	d
1	58		20	30
2	58		30	30
3	58		20	20
4	58		50	30
5	58		30	20
6		10	30	30
7		10	30	20
Dimensions in mils				

Fig. 8. *W*-band quartz image-guide Gunn-oscillator frequency as a function of the bias disk thickness and disk diameter.

the quartz guide side surface had no effect on power and frequency output until the metal block was almost touching the quartz. When the metal block touched the quartz guide top surface, slight power and frequency fluctuation was sometimes observed. We attributed that effect to phase shifting by metal block. We therefore concluded that the E_{21}^{Y} mode was not generated at a significant power level. Otherwise, radiation could occur to cause power loss when metal block was placed near the guide side wall.

V. Conclusions

A computer-controlled laser cutting technique has been successfully applied to fabricate dielectric image-guide circuits. The quartz image-guide Gunn oscillator with a packaged Gunn diode integrated in the image guide achieved useful output power and electronic frequency tuning range for a 94-GHz FMCW radar being developed. Test results indicated that the diode bias disk and pin form an *LC* resonance circuit which affects directly the oscillation frequency of the Gunn oscillator. Further circuit parameter optimization is continued, and the obtained data will be used in the GaAs monolithic image-guide Gunn-oscillator design. The monolithic Gunn oscillator is currently being fabricated by multiple layer epitaxial crystal growth using molecular beam epitaxial and metal organic chemical vapor deposition techniques.

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Design of Dielectric Grating Antennas for Millimeter-Wave Applications

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***Abstract*—A theoretical procedure well suited for generating design data on dielectric grating antennas for the millimeter-wave region is presented. The procedure utilizes the effective dielectric constant (EDC) method to determine the phase constant of the leaky modes supported by the antenna structure of finite lateral width. The radiation or leakage constant of these modes is obtained from the relatively simple boundary value problem of dielectric grating antennas of infinite width. For single-beam radiation, the practically interesting case, the phase and leakage constants completely determine the field distribution in the antenna aperture, from which the directivity gain and radiation pattern are then calculated. The dependence of the antenna characteristics on the dimensions of the radiating structure is presented and discussed for $\epsilon = 12$, the dielectric constant of typical millimeter-wave materials, such as silicon and GaAs.**

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I. Introduction

RECENT ADVANCES in the fabrication of millimeter-wave systems using integrated-circuit technology have stimulated considerable interest in the development of new antenna configurations compatible with this technology [1]–[8]. If the antenna can be integrated with other components, the cost, size, and weight of the system can be greatly reduced. A dielectric waveguide with a periodic surface corrugation has been shown to hold substantial promise as a leaky-wave antenna for millimeter-wave applications [2]–[8]. Such an antenna structure may be conveniently fabricated on a uniform dielectric waveguide to form a completely integrated millimeter-wave system. In addition, these dielectric leaky-wave antennas offer the

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