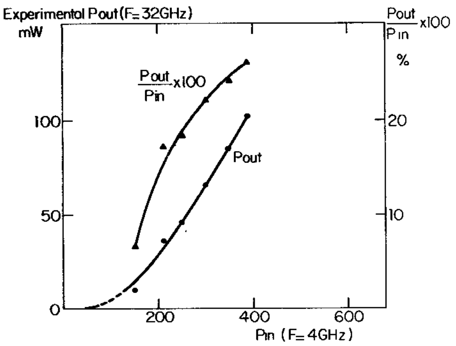

Fig. 2. Best experimental result for a GaAs diode in output power and conversion efficiency as a function of the input power in multiplication by 8 with a dc input power of 1.5 W.

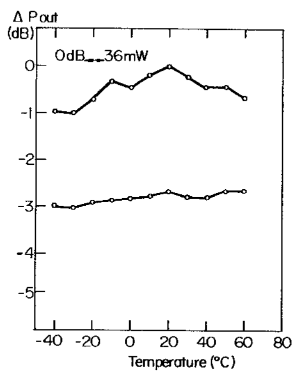

Fig. 3. Temperature dependence of the output power for two GaAs avalanche diodes in multiplication by 8 in the range −40–+60°C.

line opposite to the input (the other side of the waveguide and in the middle of the largest side of the waveguide). The coupling between this coaxial line and the waveguide is facilitated by a ridged waveguide which allows second and third harmonics to be tuned in the waveguide by means of the short circuit. Recent computer calculations have shown the importance of such a tuning control (a reactance of about $-j50\ \Omega$ is needed at the second and third harmonics viewed from the diode).

Four batches were made, and the last gave the best results which were 100 mW of output power at 32 GHz with 400 mW of input power at 4 GHz corresponding to a conversion loss of 6 dB with a dc input power of 1.5 W (Fig. 2). We have verified that this multiplication does not add noise to the input signal but only reproduces the total noise (AM + FM) with a multiplication of the frequencies in the spectrum. From a temperature stability point of view, less than 1-dB variation of output power was measured from −40 to +60°C (Fig. 3). Most of the diodes from this batch gave less than 10-dB conversion loss under the same input conditions. These results are qualitatively in agreement with the preceding computer calculations, but we think that the doping level of these diodes was too high (3.10^{16} cm^{-3} instead of 2.10^{16} cm^{-3}) and that the diameter was too large (70 μm instead of 55 μm). The greatest divergence is in the current density which is much lower experimentally than predicted.

A more versatile mount with variable tuning possibilities at the second and third harmonics is being constructed in order to improve the performance and the reproducibility. A correlation between measured impedances (seen by the diode) with those predicted by the computer will also be possible. The first experimental results obtained with high-harmonic multiplication (by 32) are encouraging because 9-dB conversion loss was obtained at 32 GHz of output frequency.

Summary and Conclusion

We think that frequency multiplication is an attractive solution for the achievement of stable output power at high frequencies (for example, *Ka* band) since stable oscillators are available at lower frequencies (lower than 4 GHz). With this idea in mind, we have chosen the avalanche multiplication process because it is capable of giving high efficiencies (6-dB conversion losses) for high multiplication orders and medium input powers with a very low sensitivity to temperature variations.

It has been shown both theoretically and experimentally that GaAs is at least as good as Si in the conditions mentioned previously. It has been demonstrated that layers which include n^+ buffer layers allow GaAs diodes to support a very high field in a reliable manner because the working temperature is very low (80°C).

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Low-Loss Broad-Band EHF Circulator

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***Abstract*—A waveguide circulator design is reported that has resulted in a structurally rugged, thermally stable circulator with exceptional RF performance. With this design, insertion loss of less than 0.1 dB, more than 20-dB isolation, and VSWR less than 1.2:1 have been achieved, each over 7 GHz of bandwidth from 27 to 34 GHz and 31 to 38 GHz.**

Introduction

The standard-height waveguide design reported here uses a double turnstile junction, which was previously identified by Owen and Barnes [1] in their explanation of circulator operation, and optimally combines RF broad-band and low-loss performance, parts simplicity, ruggedness, and temperature stability in one unit. Specifically, the following characteristics are true.

1) No epoxies or adhesives of any kind are used since all cylindrical parts are self-indexing. The result is a rugged mechanical design suitable for space applications.

2) Thermal stability was achieved by use of ferrite material (TT2-111) with low $4\pi M_s$ versus temperature variation, by junction design allowing operation with ferrites biased well into saturation and by use of high-quality rare-earth permanent magnets.

3) Two turnstile junctions separated by thin reflecting septum allow use of standard-height waveguide.

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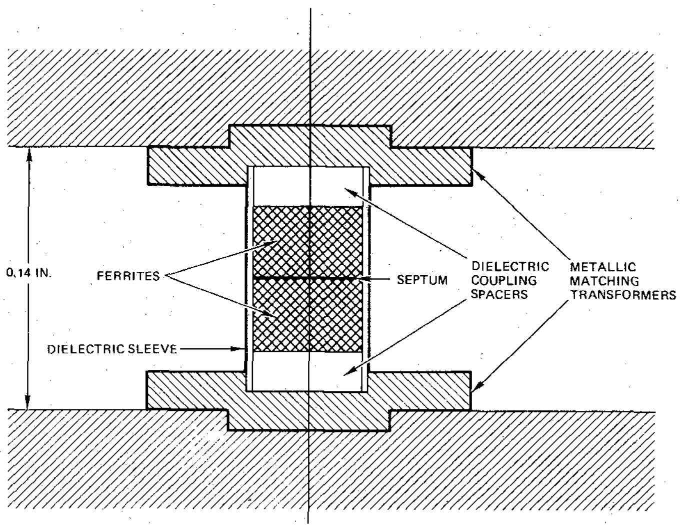

Fig. 1. Physical arrangement of broad-band waveguide circulator junction.

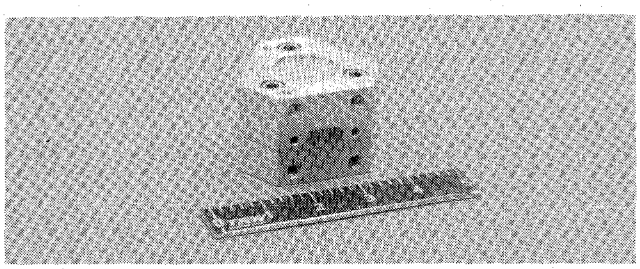

Fig. 2. *Ka*-band high-performance circulator.

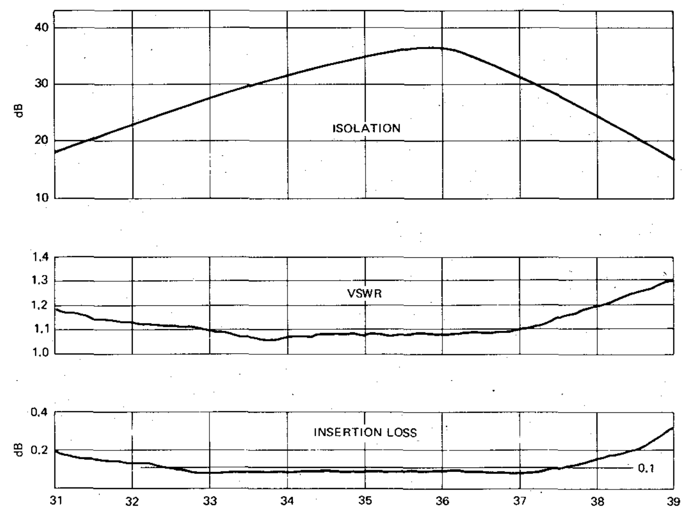

Fig. 3. Typical circulator performance (standard-height waveguide, septum type).

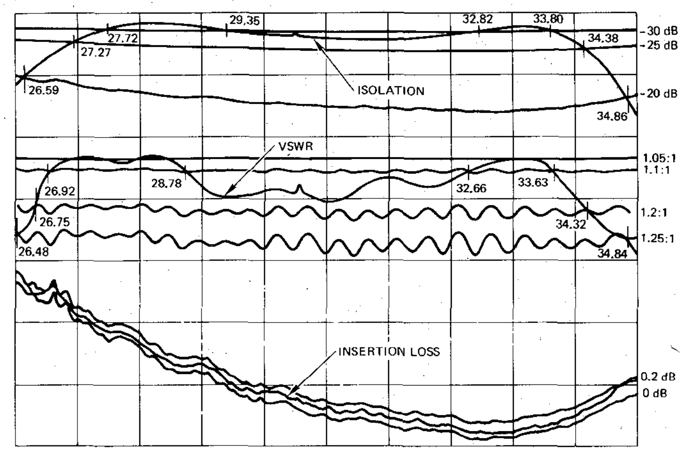

Fig. 4. Isolation, VSWR, and insertion loss of 26.5–34-GHz circulator.

The high-performance design has been developed from a reduced-height (half of standard-height guide) waveguide design employing one single ferrite. Contrary to an opinion expressed in the excellent recent paper by Helszajn and Tan [2], which suggests superiority of the single-disk geometry over multiferrite arrangements, significant improvement in circulator performance was obtained with the two-ferrite/septum design. Excellent control over the key parameters has been achieved to a point where the design has been shown to be scalable to (and yield high performance over) any 20–25-percent frequency band in the 12–40-GHz range.

Design Approach

As part of the preliminary circulator design, the length of the ferrite was arbitrarily assigned as $3\lambda/8$, considering the dielectric constant (ε_f) of the ferrite material. One end of each ferrite is short circuited by a thin reflecting septum, produced by plating one face of the ferrite cylinder, or by a copper shim (0.002 in thick). The other end of each ferrite is in contact with a dielectric spacer. The spacers may be made of any low-loss low-dielectric-constant material like Teflon or rexolite. With the assigned length of the ferrite cylinder, the diameter is not unique and a wide range of diameters, each determining the Q factor for each shape, will satisfy the requirements of circulation. The diameter of the ferrite cylinder was established experimentally to satisfy primarily the requirement of 0.1-dB insertion loss and, secondarily, a high magnetic bias level which drives the ferrite cylinders well into saturation. All configurations requiring adjustment of magnetic bias were discarded, regardless of their acceptable RF performance.

For circulator action, a $2\pi/3$ phase difference is required between two rotating modes (two circularly polarized eigen excitations propagating internal to the ferrite, each of which experiences a different effective permeability, with the propagation constants directly but nonidentically influenced by the external magnetic biasing field) and the in-phase coaxial dielectric resonator mode. In order to achieve a broad bandwidth, it is important to employ the lowest possible mode and shortest associated path length. A long path length difference would result in a narrow circulator bandwidth because the rate of phase change with frequency of the in-phase mode is much less than that of the rotating mode. Widest bandwidth is obtained by fine tuning the dimensions to achieve equal ripple Chebyshev response characteristics.

Low-loss dielectric is used to sandwich the ferrite to provide for coupling into and out of the TT2-111 ferrite. The length of this dielectric is selected so as to position the in-phase dielectric mode at the center frequency. The lowest order resonance condition is found from

$$\frac{\pi D_{\text{eff}}}{\lambda_0} (\varepsilon_{\text{eff}})^{1/2} = 1.84 \qquad (1)$$

where

- D_{eff} 1.1 × diameter of ferrite;
- ε_{eff} unknown effective dielectric constant of matching dielectric;
- λ_0 free-space wavelength.

TABLE I
SUMMARY OF CIRCULATOR PERFORMANCE ACHIEVED

Component	Parameter	Performance
Ka-Band Circulator 31 - 38 GHz	Insertion Loss	<0.1 dB
	Isolation	>20 dB
	VSWR	<1.2:1
Ka-Band Circulator 26.5 - 34 GHz	Insertion Loss	<0.1 dB
	Isolation	<20 dB
	VSWR	<1.2:1
Five-Junction Circulator 31 - 38 GHz	1-Pass Insertion Loss	<0.1 dB
	3-Pass Insertion Loss	<0.4 dB
	Isolation per Pass	>20 dB
	Input, Output VSWR	<1.2:1
Ku-Band Circulator*	0.2 dB Insertion Loss BW	13.5 - 17 GHz
	20 dB Isolation BW	12.6 - 18 GHz
	1.2:1 VSWR Bandwidth	13.6 - 17 GHz

* Scaled from 31–38-GHz basic design.

The length of the coupling dielectrics is found from the relationship

$$\frac{l_d}{l_f} = \frac{1 - \dfrac{\varepsilon_{\text{eff}}}{\varepsilon_f}}{\dfrac{\varepsilon_{\text{eff}}}{\varepsilon_d} - 1} \tag{2}$$

where

l_d length of matching dielectric;
l_f length of ferrite;
ε_{eff} effective dielectric constant, determined from (1);
ε_f dielectric constant of ferrite;
ε_d dielectric constant of matching dielectric.

Additional key design considerations affect the design of the metallic matching transformer external to the ferrite. The diameter of this transformer is equal to the diameter of the ferrite plus $\lambda_0/2$. The height of the transformer is optimized for the required performance. In general, a higher transformer results in lower isolation in the center of the band, while reducing the height of the transformer has the effect of increasing the isolation in the center of the band at slight decrease in bandwidth.

Mechanical ruggedness is achieved by stacking the five cylindrical piece parts (septum, two ferrites, and two dielectric coupling spacers) inside a thin dielectric sleeve. The sleeve is indexed to the housing via a recess in the metallic matching transformers, as clearly seen in Fig. 1. This arrangement obviates the need for epoxies or glues and additionally assures low loss. A photograph of an assembled *Ka*-band single-junction circulator is shown in Fig. 2.

Once the required magnetic field for circulation is established in the junction, significant increases of the magnetic-field strength produce only minor changes in circulator performance. Minor shifts occur only at the outer edges of the band. Fluctuations of performance caused by temperature changes are minimized since the junctions are biased by approximately twice the required magnetic field for acceptable circulator performance. This characteristic of the circulator junction presents a significant advantage over designs requiring accurate adjustment of magnetic field and where increasing or decreasing the magnetic field causes severe frequency shifts and degradation of performance. Rare-earth high-energy permanent magnets are used because their reversible loss in induction and coercivity varies such a small amount, e.g., from +0.033 percent at −100°C to −0.048 percent at +250°C. Such small changes will not produce any measurable changes in circulator performance.

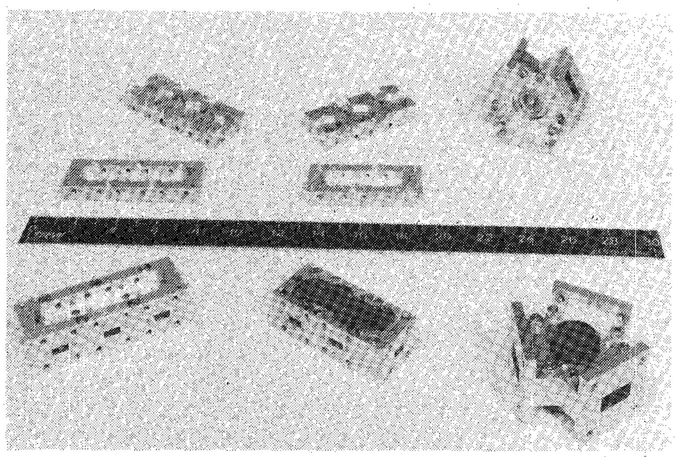

Fig. 5. Hardware derived from basic design includes four- and five-junction *Ka*-band circulator (center and left foreground) and *Ku*-band circulator (right).

EXPERIMENTAL RESULTS

Results typical of the standard-height dual ferrite/septum-type circulator design achieved are shown in Fig. 3. The exceptionally low loss typical of this broad-band design is primarily due to 1) exceptional match of the junction geometry, and 2) absence of epoxies or adhesives. As seen from Fig. 3, the VSWR is less than 1.1:1 over 4 GHz.

Once determined, the basic design was utilized in several ways: First, the design was scaled to achieve wide-band circulator performance in the lower part of *Ka* band. The broad-band results achieved are shown in Fig. 4. The quality of the basic design and level of parameter control was verified by successfully demonstrating broad-band circulator performance at *Ku* band. Further validity of the design was established by utilizing the basic design in the development of several four- and five-junction circulators. No interstage matching is required between successive junctions.

The hardware derived from the basic design are depicted in Fig. 5; a summary of the circulator performance achieved is presented in Table I.

Summary

In summary, the design approach experimental results have been presented describing a rugged temperature-stable high-performance circulator design that has proved to be scalable. These circulators are being successfully utilized in the development of broad-band solid-state amplifiers.

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Varactor-Tuned Millimeter-Wave MIC Oscillator

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Abstract—**Varactor-tuned millimeter-wave MIC Gunn oscillators have been developed using packaged devices. A tuning range greater than 1 GHz was obtained in the 35-GHz range.**

I. Introduction

Recent papers have proven the feasibility of utilizing both Gunn [1] and IMPATT [2] diodes for millimeter-wave MIC oscillators. Wide-band varactor tuning has required unpackaged (low-parasitic) generating diodes. This has led to complications in the mounting of the small heat generating chips.

In this short paper, MIC oscillators using *packaged* Gunn diodes will be described. A varactor-tuned oscillator, operating in the 35-GHz region, had a tuning range in excess of 1 GHz. A graphical analysis will show the possibility of tuning ranges of 2–5 GHz.

II. Gunn Oscillator—Description

Fig. 1 is a diagram of a varactor-tuned microstrip-mounted Gunn oscillator. The Gunn diode is a commercially available 35-mW packaged device from Varian.[1] The varactor diode is in chip form, available from Alpha with gold ribbon leads attached.[2]

The oscillator operated in the region of 35 GHz; electronic tuning was over 1 GHz. The microstrip configuration includes a single-section quarter-wave edge-coupled filter, which acts as a low-loss dc block, and low-pass filters in both the Gunn and varactor lines to inhibit RF from being conducted along power supply lines. The oscillator is constructed on copper clad ($\frac{1}{2}$ oz) Duroid. This microfiber reinforced Teflon substrate has a dielectric constant of 2.3 and is approximately 0.010 in thick. The oscillator has an output power in excess of 5 mW over a gigahertz bandwidth, sufficient for many oscillator applications.

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[1] Varian VSA 9210.

[2] Alpha CVH 2045-96.

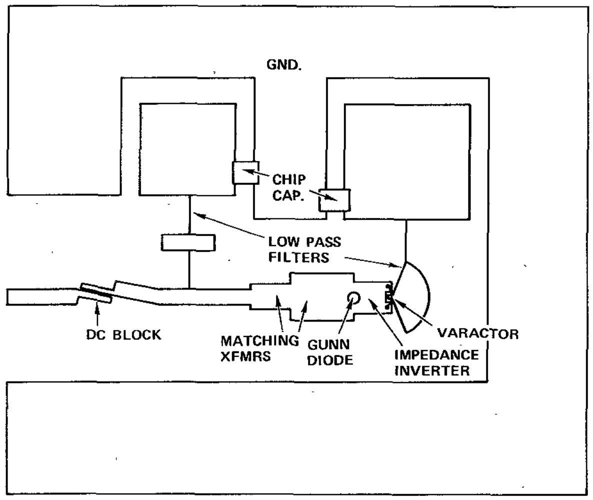

Fig. 1. Varactor-tuned microstrip oscillator.

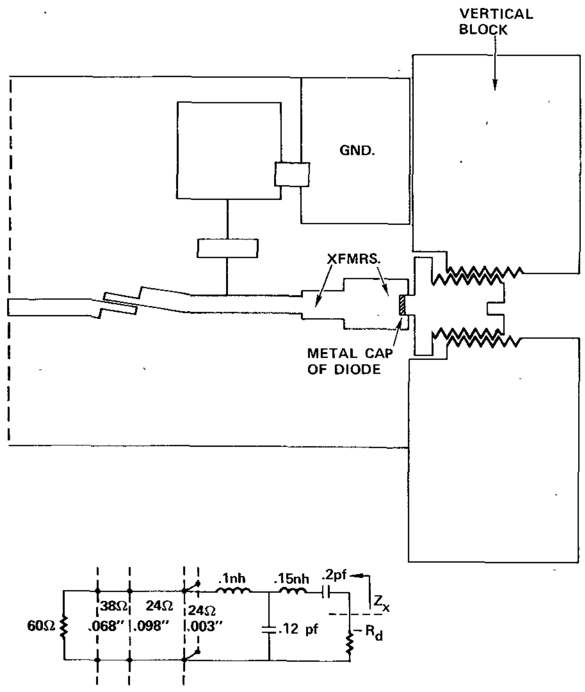

Fig. 2. Fixed-tuned microstrip oscillator. Last transformer section readily altered. Diode can be shifted slightly in position.

III. Gunn Oscillator—Design

Initially, a fixed-tuned microstrip oscillator was fabricated using a combination of experimental and analytical methods. Although a reasonable small-signal equivalent circuit of the packaged diode was available [3], the oscillator operated as a large-signal device, with a higher negative resistance and possible different dynamic capacitance, than given by the small-signal model. For the fixed-tuned oscillator, a series of various low impedance lines and matching quarter-wave transformers were constructed as in Fig. 2. The final lengths of these lines were easily altered by cutting. A Gunn diode, mounted slightly above and parallel to the line, made contact with the latter in various positions by screwing the diode heat sink more or less out of the block. In this manner, the small transmission line behind the short position was made to act as an open circuit capacitive stub, and a small amount of mechanical tuning was allowed. With very little experimentation, output powers of 30–40 mW were attained