Millimeter Integrated Circuits Suspended in the *E*-Plane of Rectangular Waveguide

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Abstract—Progress concerning a class of planar millimeter circuits is reported. The circuits are photoetched into one or more conductor layers and are suspended, with or without dielectric layers, in the *E*-plane of one or more rectangular waveguides. The class includes the integrated fin line, the planar structure introduced by Konishi, and a four-port printed-probe circuit. Such circuits feature standard waveguide flanges, printed-circuit economy, low insertion loss, wide single-mode bandwidth, and compatibility with low-parasitic hybrid devices. Furthermore, the equivalent dielectric constant can be close to unity, which is advantageous at millimeter wavelengths. The design and performance are reported of new *E*-plane millimeter components including a wide-band high-isolation low-loss SPST switch, a balanced mixer, an endfire antenna, and a four-port coupler applicable to planar channel-dropping networks. The versatility, performance, and construction features of the *E*-plane approach are relevant to advanced, highly integrated, millimeter systems.

I. Introduction

It has been demonstrated that wide-band low-loss integrated circuits can be constructed at millimeter wavelengths by inserting etched conductive sheets, with or without parallel dielectric layers, into the *E*-plane of a rectangular waveguide. This class of integrated circuits includes the fin line [1]–[3], an all-metal *E*-plane structure [4], and a printed-probe four-port coupler [5]. The advantages of such circuits include a wide single-mode bandwidth, low insertion loss, production economy, and compatibility with hybrid IC devices and waveguide instrumentation. The equivalent dielectric constant of these transmission lines can be close to unity [6]–[8] which avoids excessive miniaturization and thereby eases mechanical tolerances.

This paper reviews and updates progress with *E*-plane integrated circuits. New examples of *E*-plane components are presented to illustrate further the capabilities of this approach to millimeter IC design. The new components described include a wideband SPST switch, a balanced mixer, an endfire antenna, and a four-port forward coupler. Of particular interest is the p-i-n switch, which provides an outstanding combination of reverse-bias insertion loss and forward-bias rejection across a full (40-percent) waveguide band. Also of special interest is the coupler, whose ability to provide tight, wide-band, forward coupling in a planar format is important to the realization of low-cost channelized millimeter receivers.

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The following paragraphs describe the structure and performance features of *E*-plane millimeter circuits. The versatility of these planar circuits and their compatibility with batch processing techniques offer unique performance/cost tradeoffs which are relevant to advanced millimeter systems.

II. Fin-Line Structure

In a fin-line structure, longitudinal metal strips and dielectric layers are suspended in the *E*-plane of a rectangular waveguide housing to provide capacitive loading to the quasi-TE_{10} mode [2]. This loading widens the single-mode bandwidth as in a similar structure—ridged waveguide [9], [10]. The fin line differs from the slot line [11] in that the former has a quasi-TE_{10} cutoff frequency but does not require a high-k substrate to prevent radiation. The ability to choose low-k substrates is advantageous at millimeter wavelengths, where excessive miniaturization can lead to tolerance problems.

In early fin-line structures [2], dielectric boards were clamped between the halves of the waveguide housing. Although this is adequate for laboratory tests, a mechanically superior structure is desirable. Fig. 1 shows an improved fin-line structure which has been successfully tested under stringent environmental conditions [12], [13]. In the improved structure, the halves of the housing are bolted together in the flange region, and the dielectric boards need not be under compression. A slot in the housing along the *E*-plane provides clearance for the boards, which are aligned by Rexolite dowels. To keep Fig. 1 general, the antipodal fin-line configuration [1], [8] has been illustrated. Keeping the fins on one side of the board, of course, facilitates the mounting of chip and beam-lead devices. If the fin line is to be combined with the microstrip in a single housing [14], [15], up to four insulators may be required to prevent contact between the printed patterns and the housing. The thickness of the broad waveguide wall is chosen to be a quarter wavelength (including dielectric loading), as shown. This effectively shorts the fin to the housing at the inner edge of the broad wall and prevents radiation. The quarter-wave choke also suppresses TEM propagation by effectively connecting all conductors at the inner wall. Additional TEM suppression, where required, can be obtained by etching transverse slots into the conductor pattern within the choke region [16]. Since the fins are insulated at low

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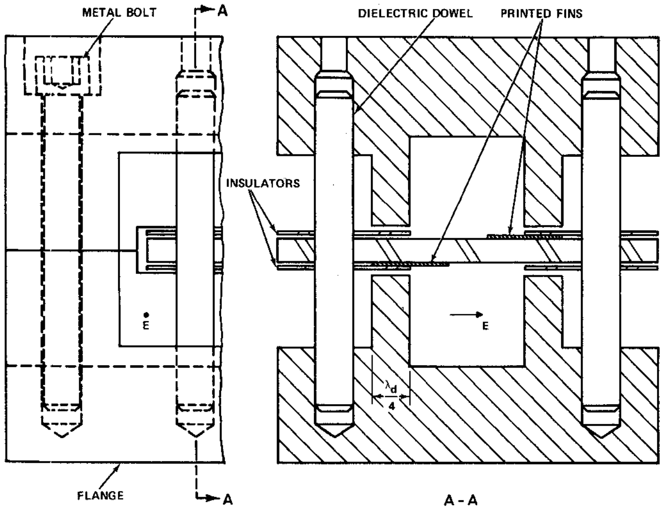

Fig. 1. Fin-line structure.

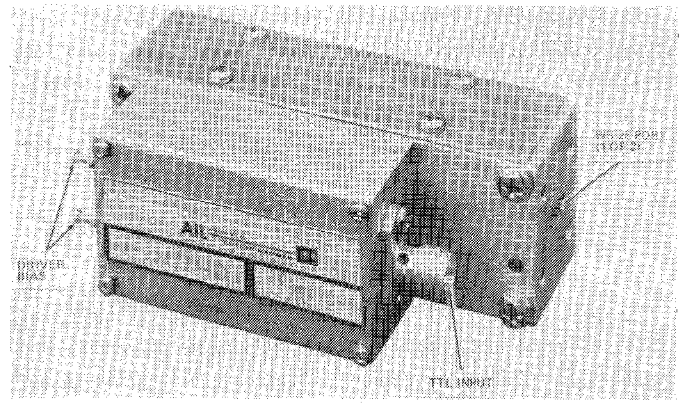

Fig. 2. *Ka*-band SPST switch with driver.

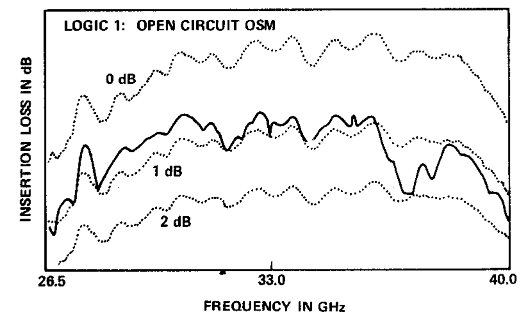

Fig. 3. Swept insertion loss of SPST switch.

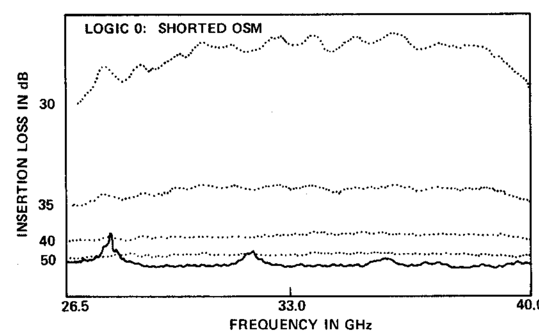

Fig. 4. Isolation versus frequency for SPST switch.

frequencies, dc bias may be injected and video/IF signals may be extracted from semiconductors mounted across the fins.

Just as single and double ridges are utilized in an all-metal waveguide [9], similar structures are feasible in a fin line. The single-fin configuration has been shown to be useful in oscillators [17] and in mixers requiring a particularly low IF bypass capacitance [16]. Another variation on the basic fin-line structure is obtained by suspending the printed board in the *E*-plane of a three-port *Y*-junction [12]. The *Y*-junction structure is not only applicable to circulators, but should prove useful in SPDT switches and negative-resistance amplifiers.

III. Solid-State Control Circuits

The *E*-plane structure, particularly the double-ridge fin line, has been successfully applied to a variety of solid-state control circuits. Examples include a two-section p-i-n attenuator in a WR-22 housing [16], [18], and a single-section p-i-n attenuator in a WR-15 housing [5]. The WR-22 design provides a forward-bias rejection of 30 ± 5 dB and a reverse-bias loss of 1.4 ± 0.2 dB across the band of 33–44 GHz. For the WR-15 attenuator, the forward-bias rejection was 20 ± 2 dB and the reverse-bias loss was 1.1 ± 0.3 dB across the band of 50–67 GHz. This author is not aware of any other p-i-n attenuators, IC or otherwise, that have demonstrated comparable performance in terms of rejection/insertion-loss across millimeter bandwidths in excess of 28 percent.

A double-ridge fin line has been recently applied to the development of a SPST switch with state-of-the-art performance across the full (40-percent) WR-28 band. Fig. 2 shows this *Ka*-band switch, which is integrated with a TTL-compatible driver. The switch contains eight commercially available beam-lead diodes which are connected across a low-impedance fin line at the center of the housing. The switch elements, consisting of single diodes or diode pairs, are spaced along the line at quarter-wave intervals. This forms a four-section design similar to the previously cited two-section attenuator [16]. The diodes are mounted in a region of the housing having the same inner dimensions as the WR-22 waveguide, and a combination of waveguide steps and fin-line tapers are provided for WR-28 interfaces at the housing flanges. Smaller waveguide housings are feasible in a heavily loaded fin line, and they have proven to be beneficial in wideband p-i-n designs.

Fig. 3 shows that the measured insertion loss of the SPST switch is typically 1 dB, and in no case greater than 1.9 dB, across the band of 26.5–40 GHz. When the TTL logic port is shorted, forward bias is applied to the p-i-n diodes and the performance is as shown in Fig. 4. The forward-bias rejection is typically greater than 50 dB, and in no case less than 39 dB across the 40-percent design band. The switching speed, measured between 90- and 10-percent transmission, is 10 ns.

In addition to electronically controlled attenuators and SPST switches, other types of solid-state control devices are feasible in a fin line. For example, an SPDT switch can be formed by placing SPST switches in two of the three arms of an E-plane Y-junction. Phase shifters can also be constructed by terminating one arm of a fin-line circulator [12] in a reflecting SPST switch.

IV. Receiver Front Ends

The E-plane integrated circuit has been proven to be useful in a variety of receiver front ends. Single-ended mixers have been constructed in a fin line and a printed monopole configuration [16]. Furthermore, the monopole mixer and a related post-mounted mixer have been embedded in planar circuits which include signal and LO bandpass filters [4], [12], [16], [19]. This approach can provide high performance through image enhancement, combined with low-cost planar reproducibility.

Balanced mixers have been constructed at centimeter wavelengths by combining slot line, coplanar line, and microstrip [20]. This technique can be extended to millimeter wavelengths, without radiation problems, by substituting a fin line for a slot line. Fig. 5 shows a recently developed balanced mixer for a radiometric application in Ka-band. The printed circuit combines microstrip, coplanar line, and fin line on a single board. The design differs from an earlier Ka-band model [14], [15] in that the structure has been ruggedized in accordance with Fig. 1, and the IF bandwidth has been increased. For presentation clarity, only two of the four insulators are shown in Fig. 5. The LO enters from the left and passes through the LO pad which is constructed from a metal-film resistance card. In addition to increasing the stability of the Gunn LO, the pad reduces the LO drive to 9 dBm, for optimum mixer performance. A printed-circuit monopole on a Duroid-5880 board provides the required transition to the microstrip, which excites the coplanar-line diode mount in the unbalanced mode. Inherent RF/LO isolation is obtained, since the diode mount is fed from the fin-line RF port in the balanced mode which does not propagate in microstrip. A printed circuit matching network is provided at the RF port for compatibility with a standard UG-599/U waveguide flange. A pair of silicon beam-lead diodes (Alpha D5600A) are bonded across the coplanar line and returned to ground at dc through LO-blocking stubs. This permits the diodes to be selfbiased and obviates the need for a regulated bipolar power supply.

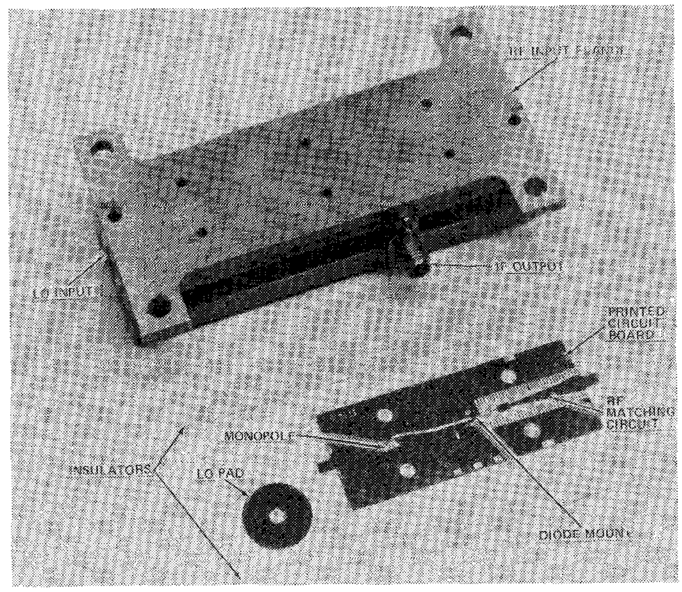

Fig. 5. Printed-circuit balanced mixer.

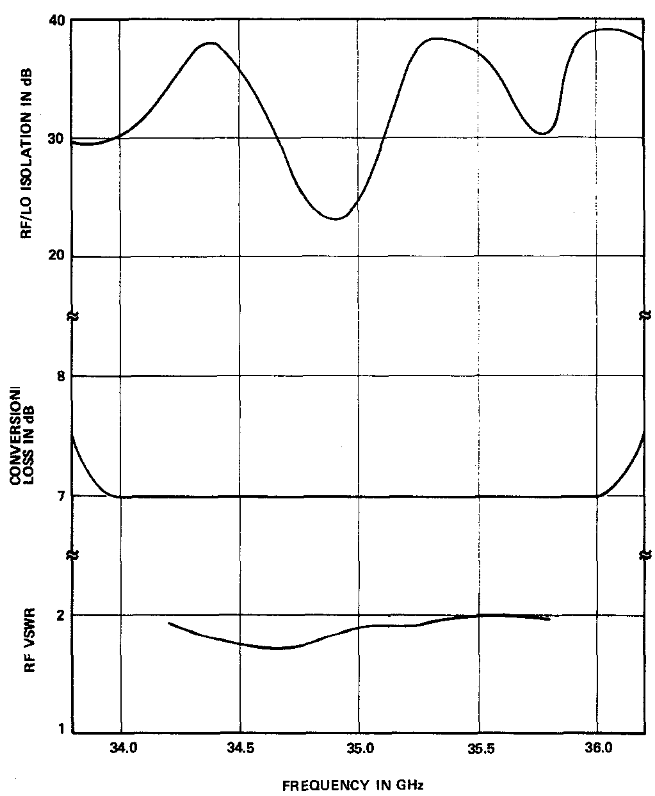

Fig. 6. Mixer performance.

The performance of the IC mixer is summarized in Fig. 6. Across a 2-GHz band centered at 35 GHz, the RF/LO isolation is 22.7 dB or better. The conversion loss, measured with the LO fixed at 35 GHz, is 7 dB across the RF band of 34–36 GHz. This shows the capability of accommodating a 1-GHz instantaneous IF band, which is well in excess of most radiometric requirements. The RF port VSWR is 2:1 or better across the design band. The measured double-sideband noise figure is 5.6 dB, including a 1.6-dB contribution from a 30-MHz laboratory IF. This agrees with the conversion-loss measurement and demonstrates that the diode excess noise ratio is essentially unity. Lower noise figures can be achieved by substituting high-cutoff GaAs diodes [15].

A further step toward the integration of a full millimeter receiver into one housing can be accomplished by including a fin-line LO. Fig. 7 shows a 31-GHz single-fin Gunn oscillator which was originally developed as a pump

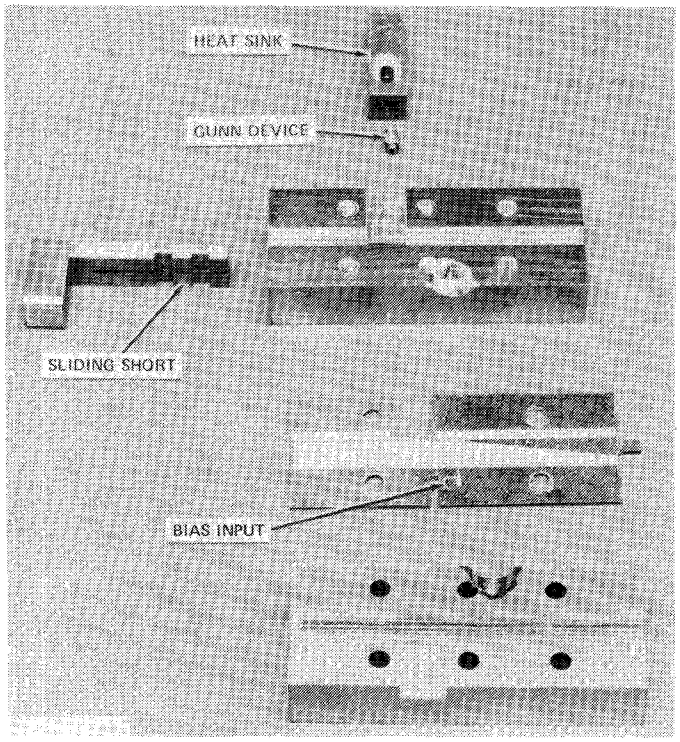

Fig. 7. Fin-line Gunn oscillator.

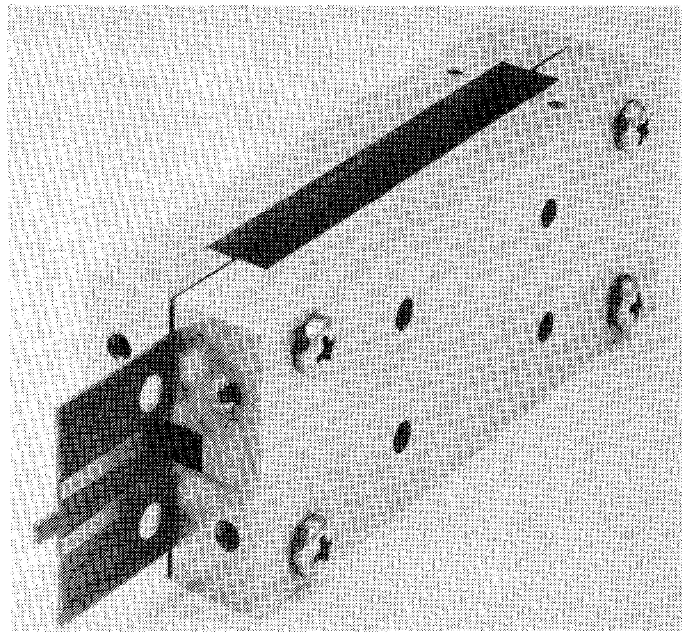

Fig. 8. Integrated fin-line antenna.

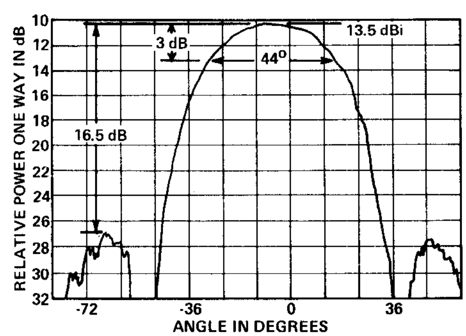

Fig. 9. H-plane pattern of fin-line antenna.

source for parametric amplifiers [17]. Since this oscillator provides a power output of 60 mW, it can drive a balanced mixer through a low-cost resistive pad. The Gunn device is threaded into a heat sink which slides into the housing and is locked in place. The center contact of the Gunn package is bonded by gold foil to the printed fin, which is biased through an RF-blocking network. The active device is terminated on the left by a sliding noncontacting short circuit which is slotted to straddle the fin-line board. The board includes a multiple-wavelength taper between standard waveguide and the low-impedance line in which the Gunn device is mounted.

Work is now in progress to scale the fin-line oscillator design to higher frequencies [27].

V. Antennas

Integrating an antenna with a receiver can provide advantages in terms of size, weight, and production cost. Such integration is especially desirable when a large number of antenna/receiver modules are required, as in a phased array or multichannel direction-finding system. It will be shown that the E-plane approach is applicable to millimeter antennas as well as receiver components.

Fig. 8 shows a 35-GHz antenna that was constructed in a fin line by extending the printed card beyond the housing. In this configuration, the fins provide an endfire radiation pattern whose shape can be varied by altering the printed-circuit geometry and the housing aperture. (A WR-28 housing of uniform cross section was utilized in this demonstration.) The H-plane radiation pattern of the fin-line antenna is shown in Fig. 9. The measured gain is 13.5 dBi, which is well above the level that would result from a WR-28 aperture without the endfire circuit. The half-power beam widths are 44° in the H-plane, and 27° in the E-plane. A simple fin-line taper between the aperture and the waveguide feed provides an input VSWR of 1.8 or better across a 4-GHz band centered at 35 GHz. It is believed that wider bandwidths are feasible with a multipole printed matching circuit.

E-plane circuits are also applicable to another type of antenna. It is well known that a narrow-beam antenna can be constructed by cutting an array of radiating slots into a rectangular waveguide [21]. A similar array of radiators could be formed by slotting the broad wall of a waveguide and inserting a board printed with an array of coupling probes. The structure would be similar to the printed-probe coupler [5], except that each probe would radiate into space, rather than a parallel waveguide.

E-plane structures are applicable to a variety of antenna configurations; they feature printed circuits in axially uniform housings, and allow active and passive circuits to be closely integrated with antennas at millimeter wavelengths.

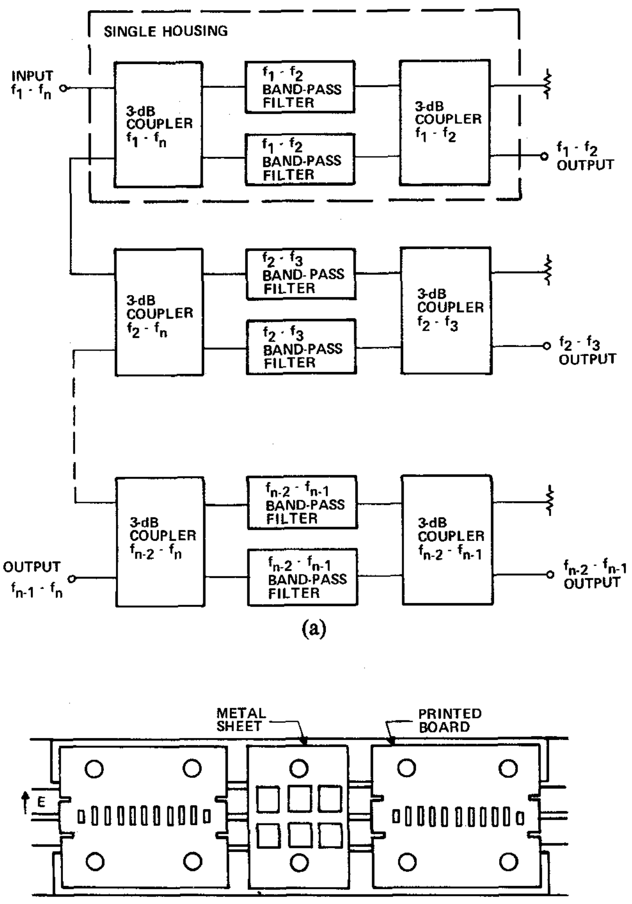

Fig. 10. multiplexer. (a) Network. (b) Housing cross section.

VI. Planar Filters

Bandpass filters have been developed at centimeter and millimeter wavelengths by placing conductive strips in the E-plane of a rectangular waveguide. The planar structure can be a perforated metal sheet [4], [5], [22], [23] or a printed circuit with a dielectric backing [2], [16], [19]. The all-metal structure provides a higher Q, whereas the metal/dielectric approach allows close integration of filters with semiconductor mounts (including printed bias networks). Measurements of unloaded resonator Q for the all-metal structure show typical values of 2500 at 12 GHz [4] and 1600 at 32 GHz [5]. Since the Q of this type of structure has been shown to vary inversely with the square-root of frequency, a Q on the order of 900 appears feasible in the 3-mm band.

In addition to serving as two-port preselectors, planar filters can be combined with planar couplers [5] to form multiport channel-dropping networks. Fig. 10(a) shows a network for providing a number of contiguous-band outputs from a wideband input. A single housing, split along the common E-plane of two parallel waveguides, can accommodate printed-probe couplers and planar filters in an integrated subassembly as shown in Fig. 10(b). A key component in the network is a planar forward coupler—the final topic of this paper.

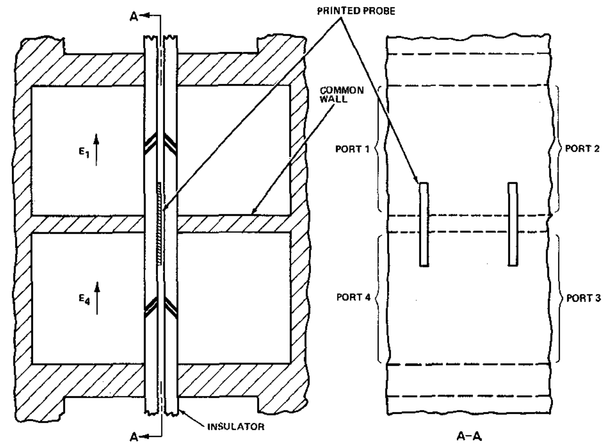

Fig. 11. Printed-probe four-port network.

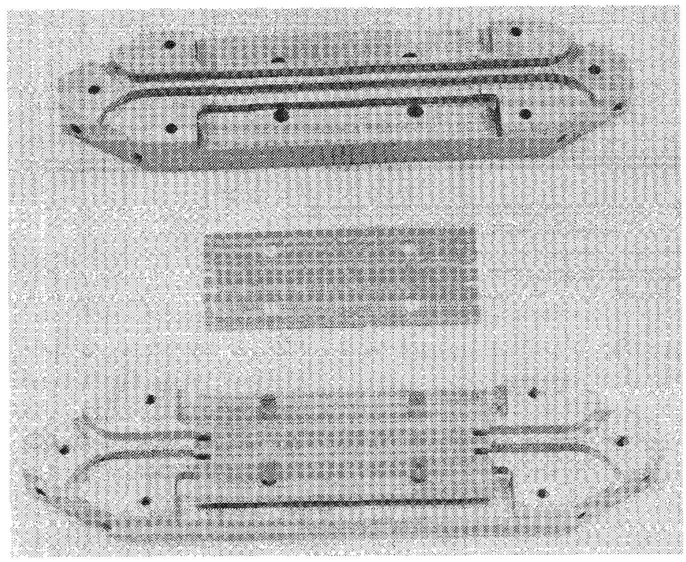

Fig. 12. Printed-probe coupler.

VII. Printed-Probe Coupler

Preliminary work toward the development of E-plane forward directional couplers has been reported [5]. The following paragraphs review this work, present additional design information, and report progress toward achieving tight (3-dB) wideband coupling.

Fig. 11 shows the construction features of the E-plane four-port coupler. In this configuration, two parallel waveguides share a common broad wall which is slotted along the E-plane to accept a pair of dielectric boards. Directional coupling between the waveguides is obtained by an array of probes which is printed on one of the boards. The other board centers the probes in the slot and insulates them from the common wall. Radiation from either of the outer broad walls is negligible because the slot is centered, and the wall thickness is chosen to be a quarter wavelength in the dielectric (as in the fin line).

Fig. 12 shows a four-port housing which was constructed to demonstrate the feasibility of the printed-probe coupler. The housing was fabricated in two parts

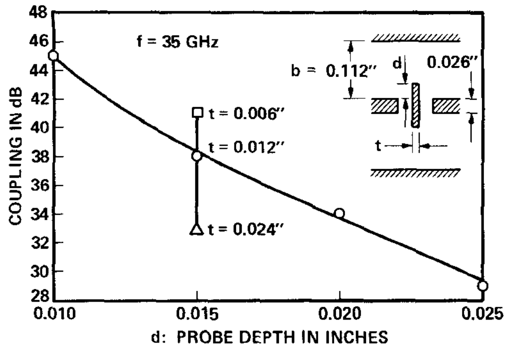

Fig. 13. Coupling versus probe depth.

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A B C B A
      A B C B A
            A B C B A
                  A B C B A
+                       A B C B A
A B C C C C C C C C C C C C C B A
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VOLTAGE RATIOS FOR 5-ELEMENT TCHEBYCHEFF ARRAY:

A = 1.000 B = 2.835 C = 3.840

$A + B \approx C$

FOR 17-ELEMENT ARRAY: 2A + 2B + 13C = 57.55

-35.2 dB < COUPLING < -23.5 dB (0-dB COUPLER)

Fig. 14. Superimposed coupling array.

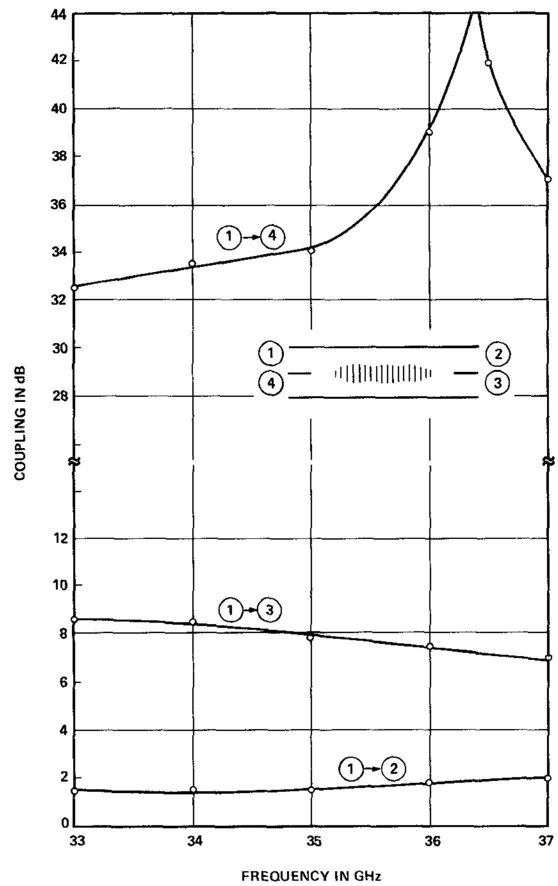

Fig. 15. Printed-probe coupler performance.

with E-plane symmetry and it incorporates four waveguide bends for compatibility with WR-22 instrumentation. The edges of the dielectric boards contain quarter-wave notches to provide an impedance match between the air-filled and slab-loaded waveguides. The boards are aligned by Rexolite dowels which are external to the broad walls of the waveguides. The housing was tested by measuring the input VSWR and the coupling to the other ports with blank (unclad) boards. Across an 11-percent band centered at 35 GHz the input (port 1) VSWR was 1.15 or better, the forward isolation (to port 3) was 27 dB or better, the reverse isolation (to port 4) was 42 dB or better, and the insertion loss (to port 2) was 0.5 ± 0.1 dB.

The design of a multiprobe directional coupler began with measurements of the coupling provided by a series of boards, each containing a single probe. By measuring the (bidirectional) coupling for probes of various dimensions, a preliminary "design library" was compiled for single-probe coupling levels of 29–45 dB. Fig. 13 shows how the coupling varies with respect to the depth and thickness of the probe at a frequency of 35 GHz.

Based upon well-known techniques [24], a multielement array was designed to demonstrate the capability of achieving moderately tight coupling and high directivity. Fig. 14 shows the array chosen for this demonstration—a 17-element array formed by superimposing a series of 5-element Chebycheff arrays. This configuration was chosen for its inherent simplicity (all 13 of the central elements have equal coupling) and the agreement between the required and known (Fig. 13) coupling values.

Fig. 15 shows a summary of the performance of the 17-element printed-probe coupler. Across an 11-percent band centered at 35 GHz, the forward coupling is 7.75 ± 0.75 dB and the directivity is 24 dB or better. Since the input is well matched (VSWR $\leqslant 1.19$) and negligible power reaches port 4, the insertion loss may be calculated by adding the fractional power in ports 2 and 3. Such a procedure shows the insertion loss to be 0.6 ± 0.1 dB, which is only 0.1 dB greater than the fixture loss without probes.

To address the wide band multiplexer application (Fig. 10), it is necessary to increase the coupling to 3 dB and reduce the variation of coupling with respect to frequency. Although tighter coupling can be achieved by a simple increase in probe depth, a compensation technique is required to offset the monotonic increase in coupling with frequency that results with a simple capacitive element. Fig. 16 illustrates various probe shapes which provide the required compensation by adding series inductance. Such shapes have long been applied to nonplanar wide-band probes [25].

Swept frequency measurements of coupling have been performed to evaluate several probe geometries, including those with series inductance. Fig. 17 shows how the

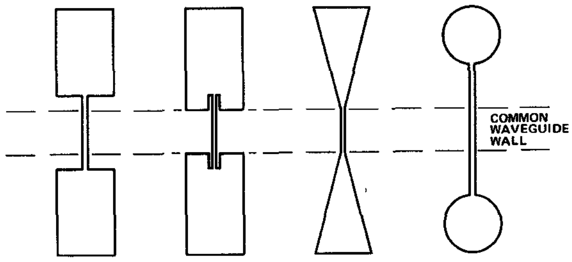

Fig. 16. Compensated probes.

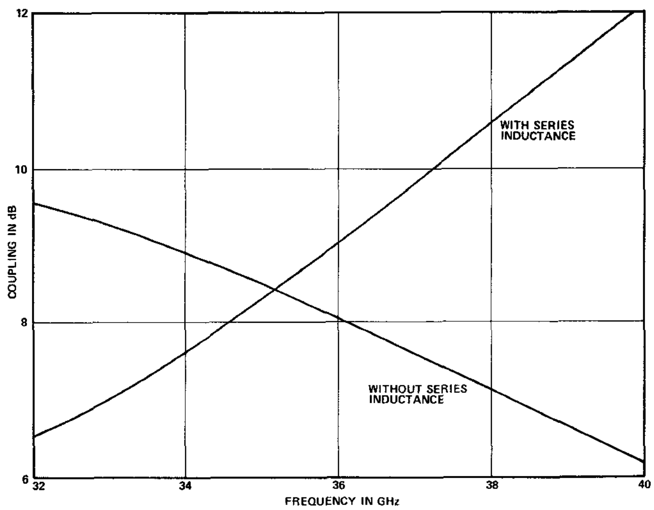

Fig. 17. Printed-probe frequency compensation.

measured coupling varies with respect to frequency for two different probe configurations. Both configurations feature a large probe depth ($d/b=0.45$) to provide tight coupling. Near the center of the band of 32–40 GHz (which is common to the WR-22 housing and a standard sweep generator), the coupling for both configurations is 8.3 dB—tighter than required for a three-element 0-dB coupler. In addition to demonstrating tight coupling, the swept measurements show that the coupling/frequency slope can be reversed with series inductance. Since the series inductance can be decreased by widening the printed line at the center of the probe, it should be feasible to obtain a relatively flat coupling across a wide frequency band. Work is now in progress to characterize inductively compensated probes and develop a wide-band 3-dB coupler.

VIII. Conclusion

The E-plane integrated-circuit approach offers advantages at millimeter wavelengths which include wide single-mode bandwidth, low insertion loss, production economy, low equivalent dielectric constant, compatibility with hybrid IC devices, and simple transitions to waveguide instrumentation. The approach has been shown to be applicable to a wide variety of components including electronically controlled attenuators and switches, mixers, oscillators, antennas, circulators, filters, and directional couplers. The versatility, calculable performance [7], [8], [26], and construction features of E-plane circuits provide opportunities for the development of a new generation of low-cost integrated millimeter systems.

Acknowledgment

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Hybrid Integrated Frequency Multipliers at 300 and 450 GHz

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***Abstract*—300- and 450-GHz band doublers and triplers using thin-film integrated circuits have been developed. The multipliers are built with a GaAs honeycomb-type Schottky barrier diode designed to have a high cutoff frequency and transitions from microstrip to rectangular waveguides.**

A 450-GHz band tripler delivered an output power of −11.2 dBm with a corresponding conversion loss of 19.4 dB. The output power of the 300-GHz band doubler was −3.6 dBm, and its minimum conversion loss was 10.7 dB.

The hybrid integrated frequency multipliers are useful as solid-state sources in the short-millimeter-wave and submillimeter-wave regions.

I. Introduction

RECENTLY, there has been an increasing need for short-millimeter-wave and submillimeter-wave solid-state sources for use in radio astronomy, plasma diagnostics, spectroscopy, and target acquisition raders.

Frequency multipliers which are driven by IMPATT or Gunn oscillators are useful sources for these applications. Multipliers which deliver useful power levels have been developed up to the 300-GHz band [1]–[3]. However, in the higher frequency region, it is difficult to fabricate multipliers using conventional fabrication techniques because of the necessity of an extremely small tolerance. We have solved this difficulty in the 300- and 450-GHz regions using thin-film integrated-circuit techniques which were used for the millimeter-wave mixers up to the 230-GHz region [2], [4], and obtained good multiplication performances.

The hybrid integrated frequency multipliers have the following advantages: 1) an easy and high accuracy fabrication method in comparison with conventional mechanical techniques, 2) possibilities of a compact and reproducible circuit design by using microstriplines, and 3) a possibility of realizing the devices at still higher frequencies [5], [6].

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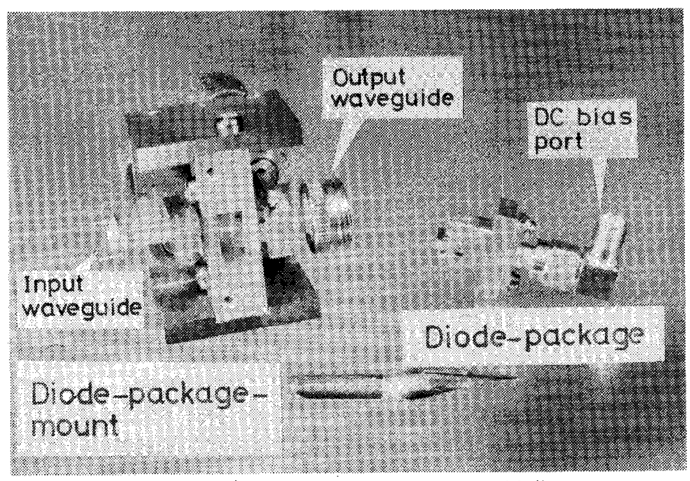

Fig. 1. Hybrid integrated frequency multiplier.

II. Design and Fabrication

A photograph of the hybrid integrated frequency multiplier is shown in Fig. 1. It consists of the following three main parts: 1) a diode-package mount, 2) a diode package, and 3) a diode chip.

A. Diode-Package Mount

The diode-package mount consists of an input 150-GHz band waveguide (WR-6), an output 300-GHz band tapered waveguide (reduced WR-3), input and output short pistons, and micrometers for driving them. Input and output waveguides were realized as short as possible