theoretically and experimentally, compared with the dominant E_{11}^y mode rectangular dielectric image line. The E_{11}^x mode attenuation constant was found to be nearly half that of the E_{11}^y mode in the 50-GHz range.

A bandpass filter, using the E_{11}^x mode rectangular dielectric image line, was fabricated and measured. Its frequency response was found to have reasonable characteristics, although radiation loss limited the achievable insertion loss. This image line device is believed to be useful for millimeter-wave integrated circuit applications.

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Millimeter-Wave Image-Guide Integrated Passive Devices

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Abstract—**Millimeter-wave boron-nitride image-guide integrated passive devices such as couplers, detectors, and balanced mixers have been developed with performances comparable to their metal waveguide circuit counterparts.**

I. INTRODUCTION

THE DIELECTRIC image guide, formed by placing the half-height rectangular cross-sectional dielectric guide on the metal plane, exhibits low propagation loss at millimeter-wave frequencies. Directional couplers, electronic phase shifters, filters, and active and passive devices of image-guide integrated circuit forms have been recently developed [1]–[4].

Complex millimeter-wave integrated circuit structures can be easily formed from dielectric materials using sandblasting, machining, laser cutting techniques, and even casting. They are a low-cost approach to millimeter-wave circuits compared to metal waveguide circuits which require precision machining, especially at frequencies beyond 60 GHz.

Boron nitride has been used successfully by us as the image-guide material for both active and passive circuit integration [1]. This paper reports our results on the loss characteristics of the boron-nitride material and on the boron-nitride image-guide integrated circuits (BNIGIC) passive devices such as couplers, detectors, and balanced mixers for use in communications and radar systems.

II. BORON-NITRIDE IMAGE-GUIDE CHARACTERISTICS

Boron nitride (BN) has a dielectric constant between 4.10 and 3.97, depending on the direction of pressing as measured by us at 53.84 GHz. Dielectric loss of the material in the millimeter-wave frequency spectrum was determined by measuring the line loss of a 2-in section of a dielectric waveguide made of BN. Fig. 1 shows the

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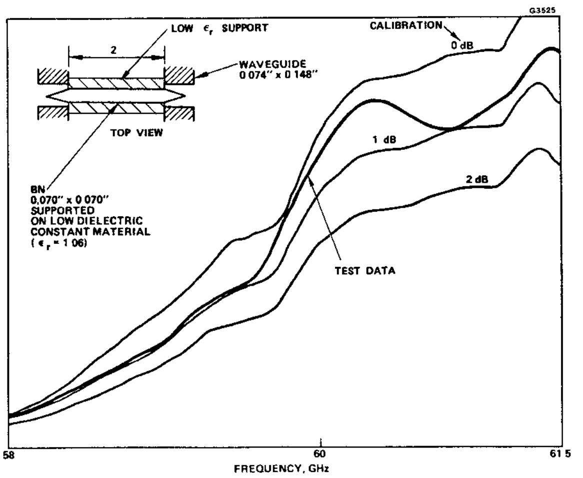

Fig. 1. Insertion loss of BN waveguide at 60-GHz frequencies.

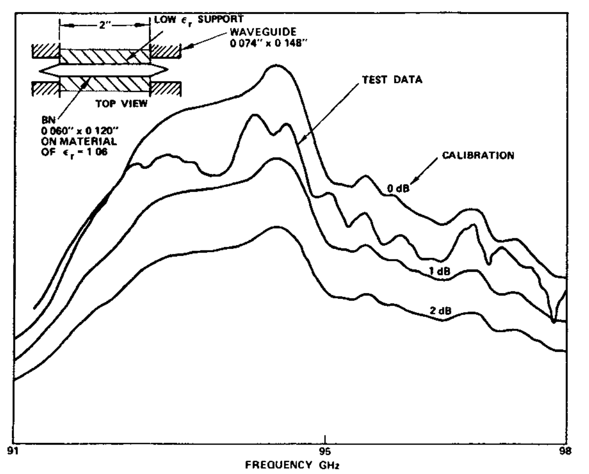

Fig. 2. Insertion loss of BN waveguide at 94-GHz frequencies.

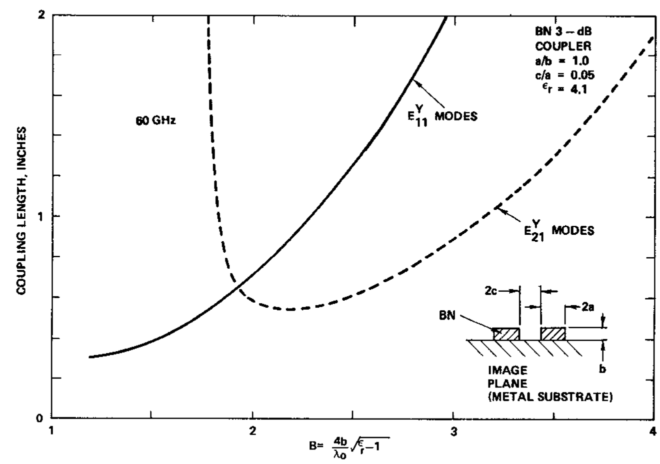

Fig. 3. BN 3-dB coupler coupling length as a function of the normalized guide height B at 60 GHz.

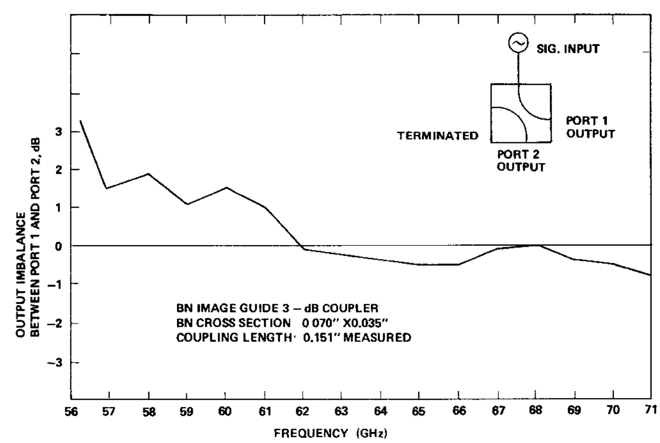

Fig. 4. Coupling characteristics of a BN image-guide 3-dB hybrid coupler.

measured data at 60 GHz. The loss measured includes the two waveguide-to-image-guide transitions, which were formed by simply inserting the tapered section of the dielectric guide into the full-height waveguide openings. The dielectric guide was supported by a low-loss material of a dielectric constant equal to 1.06 to minimize field leakage into the supporting material. The overall loss which varies between 0.2 and 1.0 dB, verifies the low-loss characteristic of the material. Fig. 2 shows the loss results obtained between 91 and 98 GHz.

III. Boron-Nitride Couplers

Dielectric image-guide couplers can be constructed by simply placing two guides close to each other. The 3-dB 90° hybrid couplers are of specific interest for balanced mixers. Fig. 3 shows the theoretical coupling characteristics of a 3-dB hybrid coupler at 60 GHz with an aspect ratio of each guide equal to 1 ($a/b = 1.0$) and a separation distance of $c/a = 0.05$ [3]. As the guide height increases for a given aspect ratio, the coupling length increases for the fundamental E^y_{11} modes (coupling between symmetric E^y_{11} and asymmetric E^y_{11} modes) due to increasing energy confinement in the individual guides. Below a value of $B \approx 1.8$, the first higher order symmetric and asymmetric E^y_{21} modes are cut off. For $B > 1.8$, higher order modes can propagate in the individual guides, and coupling between higher order modes becomes possible at shorter coupling lengths than for fundamental modes. Therefore, the optimal design finds the guide dimensions such that the E^y_{21} modes are near cutoff.

The test results of an image-guide configuration of the 3-dB coupler from 56 to 71 GHz are shown in Fig.4. This coupler shows amplitude tracking of ± 1 dB over at least 10 GHz between 61 and 71 GHz. However, this configuration had higher loss than the dielectric waveguide type. Including transition losses, an overall loss of about 1.5 dB was obtained with a minimum value of 0.8 dB at 69 GHz. Fig. 5 shows the photograph of the image-guide coupler in its test fixture.

IV. BNIGIC Detectors

Several detectors were designed and evaluated with a variety of detector diodes in BN image-guide circuits. The basic circuit for the detectors is shown in Fig. 6. The transition region from waveguide to image guide is similar to that used for the loss measurements. A metallized

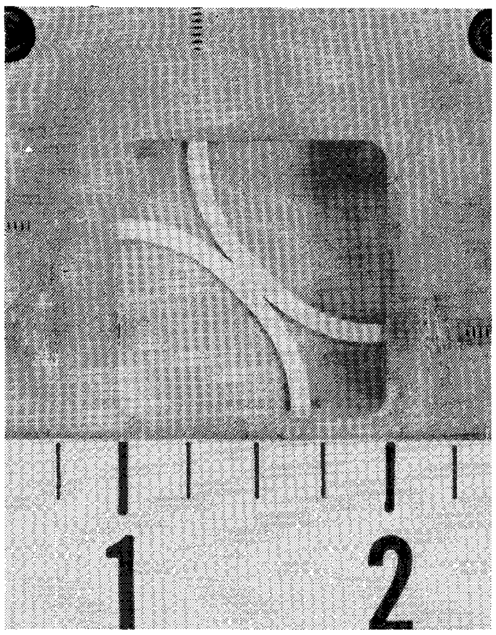

Fig. 5. Photograph of a 60-GHz BN 3-dB hybrid coupler.

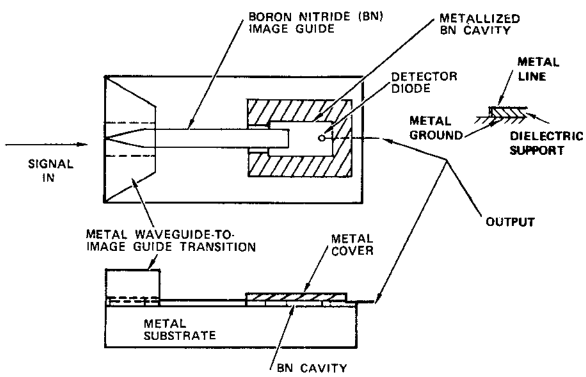

Fig. 6. BNIGIC detector configuration.

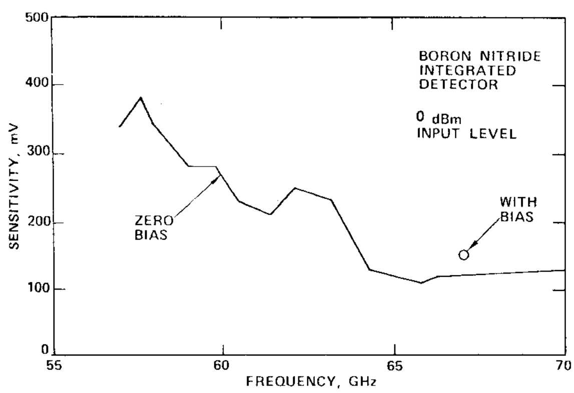

Fig. 7. BN integrated detector performance characteristics.

dielectric cavity region with a metal cover houses the detector diode, and the detected output is taken out at the rear of the cavity. Fig. 7 shows the test results for the integrated detector using beam-lead Schottky diodes.

The detector sensitivities varied because of the loss and mismatch at the waveguide-to-image-guide transitions and the effects of the diode circuit parasitics. With a slight detector bias, the detector sensitivity was moderately improved. Tangential sensitivity was measured and found to be -40 dBm. Tangential sensitivity close to -50 dBm was obtained with similarly constructed BNIGIC detectors at frequencies of 22 and 35 GHz. The results were equal to metal waveguide detector performance evaluated in the laboratory.

The detectors are very broad band. They cover more than a full waveguide band, indicating reasonable circuit matching between the device and the image guide. The metal cover, placed over the cavity section, improved the overall response of the detector by less than 1 dB. The detectors have fast video responses. Pulses as short as 10 ns or less can be detected.

V. BNIGIC Balanced Mixers

BN image-guide balanced mixers were constructed with the LO and the signal coupled into a 3-dB BN hybrid coupler through two waveguide-to-image-guide transitions and with the GaAs Schottky beam-lead diodes mounted at the two output ends of the coupler. IF output lines were printed on the BN substrate and brought out to a preamplifier as shown in Fig. 8. An air filled cavity surrounded the mixer diodes to provide approximately 1/4-wavelength terminations behind each diode. Metal covers were placed over the cavity sections; however, these covers only improved the mixer noise figure by about 1 dB, indicating that the coupling into the diodes was quite good. The noise figure of the commercial mixes preamplifier was 3.5 dB, and the IF response was from 10 to 1200 MHz.

Two mixers were constructed, one for use near 60 GHz and the other near 70 GHz. External BNIGIC Gunn local oscillators were later attached to the mixers, but noise figure data was taken using a klystron LO and a calibrated noise tube. The klystron was tuned over a large frequency range while measuring the noise figure across the band. Figs. 9 and 10 show the noise figure results of the 60- and the 70-GHz mixers, respectively. The best result was about a 11.5-dB DSB noise figure near 69 GHz. In general, the mixers exhibited bandwidths in excess of 5 GHz. LO–RF isolation for both mixers ranged from 15 to 20 dB.

The noise figures obtained were determined largely by the commercial mixer diodes. According to the manufacturer-supplied data, these diodes should have a cutoff frequency around 750 GHz (with a series resistance of 3.7 Ω and a capacitance of 0.06 pF).

Integrated mixers at 94 GHz have also been constructed in an image guide using BN. Thus far a DSB noise figure of 14 dB is the best achieved using the same diodes. The construction is essentially a scaled-down version of the 70-GHz design. Fig. 11 shows a photograph of the 70-GHz balanced mixer with an integrated BN Gunn LO attached. The balanced mixers–Gunn LO's have been used in 60–70-GHz radio communication sets and in a 94-GHz radar receiver receiving pulses as short as 5-ns pulsewidth.

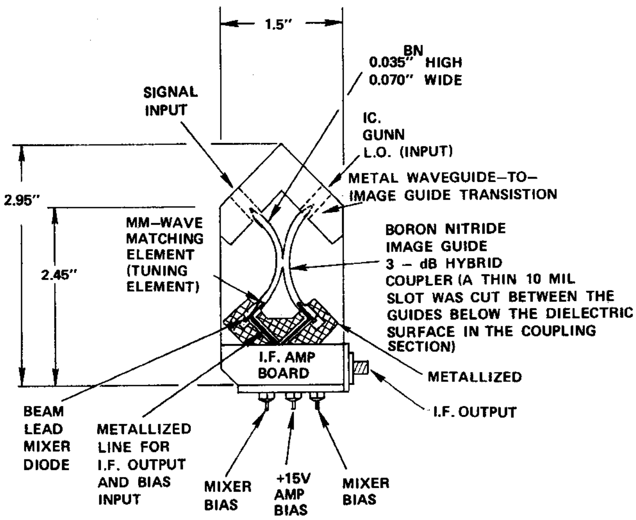

Fig. 8. BNIGIC balanced mixer circuit.

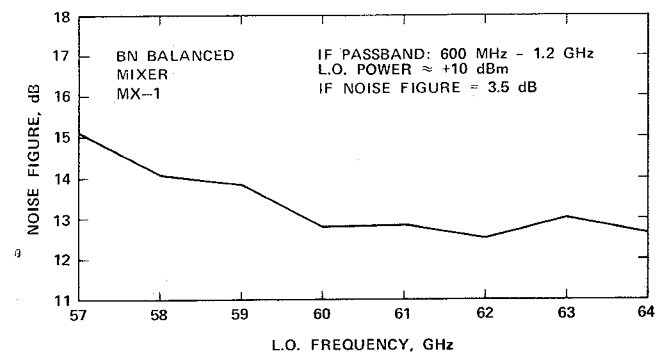

Fig. 9. Noise figures as a function of LO frequencies of the 60-GHz BNIGIC balanced mixer. Tuning elements epoxied in place.

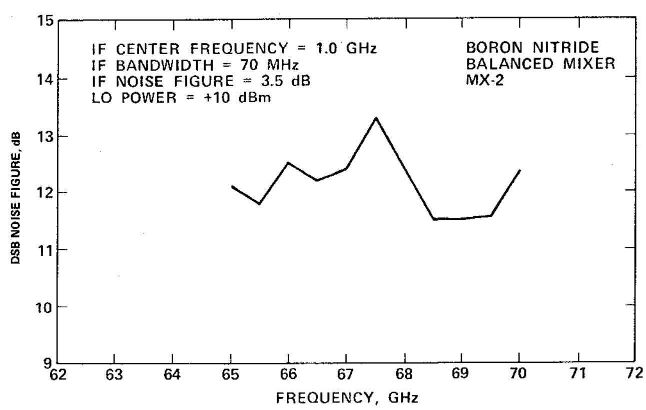

Fig. 10. Noise figures as a function of LO frequencies of the 70-GHz BNIGIC balanced mixer.

Better beam lead mixer diodes with cutoff frequencies higher than 1000 GHz are available commercially. We feel that the mixer diodes used were fundamental in determining the balanced mixer noise figure, since the BNIGIC itself showed circuit flexibility in matching with various devices. The mixers were broad band, covering between 7 and 10 GHz at all millimeter-wave frequencies tested by varying the local oscillator frequency. We expect to achieve full waveguide-band coverage with these mixers in the near future.

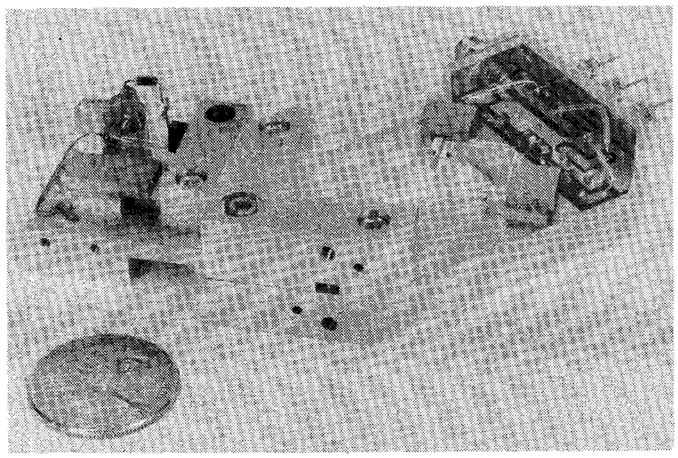

Fig. 11. Photograph of a BNIGIC balanced mixer with a BNIGIC Gunn LO attached.

VI. Conclusions

The results reported here indicate good performance characteristics of BNIGIC passive devices, expecially couplers, detectors, and mixers for potential broad-bandwidth applications at frequencies above 60 GHz. Integrated multifunctional circuit modules including passive and active devices are, therefore, feasible to reduce the cost of the metal waveguide circuits at these frequencies.

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