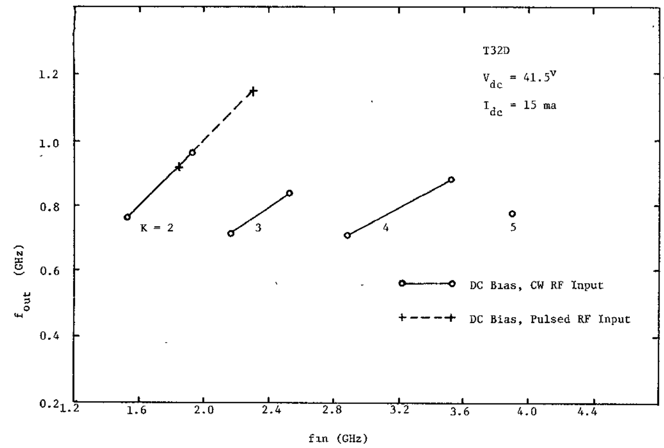

Fig. 4. Input–output frequency relation for TED T32D with indicated biasing condition. Data points between two O or two + are continuous.

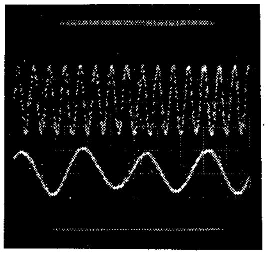

Fig. 5. Sampling scope waveforms of divide-by-4 operation. Horizontal: 0.5 ns/div; vertical: 100 mV/div; f_{in} = 3 GHz; f_{out} = 0.75 GHz.

GHz, respectively. f_D increase under the pulse-bias condition was observed also by Takeuchi *et al.* [4]. From Fig. 4, f_D was estimated to be 0.96 GHz.

A pulsed RF signal was also applied to the TED. The pulsewidth was 1 μs with a rate of 5.9×10^4 pulses/s. The actual divide-by-2 region was shifted upward in frequency as shown in Fig. 4. This was probably due to the shortening of the device transit time.

This experimental evidence indicated that f_D was a critical function of RF input power and bias condition. The results follow the temperature–electron-velocity relation of [5]. However, the exact physical mechanism was not known. The RF power measured at the input of the TED was 26 and 17 dBm at frequencies of 1.8 GHz and 3 GHz, respectively; however, the input of the TED was not matched to 50 Ω. Therefore, the triggering voltage applied to the input of the TED was not known. The conversion loss was estimated to be about 20 dB or greater. It is desirable that frequency division can be performed with gain. Hence further understanding and development of the TED are necessary for utilizing its full capacity and potential.

CONCLUSION

Frequency division by an integer K (K = 2, 3, 4, and 5) has been demonstrated using planar TED's in resistive circuits. The theoretical maximum output frequency of a divide-by-K circuit and the absolute bandwidth over which the input signal will be divided by K is the device transit time frequency. The percentage bandwidth is $200/(2K - 1)$ percent.

It has been pointed out that the domain trigger sensitivity is greatly enhanced by triggering a domain from a Schottky-barrier gate [3], [6], [7]. With optimization in TED device (including load resistor) design and fabrication, microwave frequency (up to 50 GHz) division with gain is possible. Subsequently, many applications (for example, the phase-locked loop of a microwave synthesizer) can be found for the TED frequency divider.

ACKNOWLEDGMENT

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A Broad-Band 40–60-GHz Balanced Mixer

A. HISLOP AND R. T. KIHM

***Abstract*—A wide-band fixed-tuned millimeter-wave balanced mixer covering 40–60 GHz is described. Conversion loss of 8.5 dB ± 1 dB from 40–58 GHz was obtained using unencapsulated silicon Schottky-barrier diodes.**

This letter describes the design and measured performance of a fixed-tuned, broad-band balanced mixer covering the 40–60-GHz frequency band. A rapid-scan wide-band low-noise receiver front end was a principal objective of this work. To the authors' knowledge, a broad-band mixer for this band has not been reported previously in the literature.[1] The performance achieved in the work reported here results from the use of a frequency insensitive hybrid junction and high-cutoff-frequency silicon Schottky-barrier chip diodes. [1]–[3].

The design approach uses unencapsulated Schottky-barrier mixer chips mounted in a suitable RF hybrid structure in order to achieve a balanced mixer. Unpackaged diodes were selected to maximize bandwidth by eliminating the parasitic reactances of the packages. The RF hybrid is a symmetry-type junction between reduced-height TE_{10} rectangular waveguide (0.188 in × 0.094 in) and dielectric-supported air strip transmission line in a below-cutoff channel [4]. The configuration is shown in Fig. 1. Assuming perfect electrical balance, infinite isolation between signal and LO would result. The diode chips are bonded to the conductors on the dielectric with silver-conducting epoxy. The diode junction capacitance is $\simeq$0.03 pF and $R_s \simeq$ 10–12 Ω. The chips are 15 mil square and 7 mil thick.[2] 1-mil-diam wire approximately a quarter-wavelength long at 40 GHz connects each conductor to the mount, providing a dc return for the diodes. The contacting whisker inductance series resonates

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[1] After submission of the original manuscript, the authors have received and tested a fixed-tuned mixer covering most of the 40–60-GHz band, developed by Spacekom, Inc., under contract to the Navy. This mixer used encapsulated GaAs Schottky-barrier diodes.

[2] Purchased from Hughes Electron Dynamics Division, Torrance, CA.

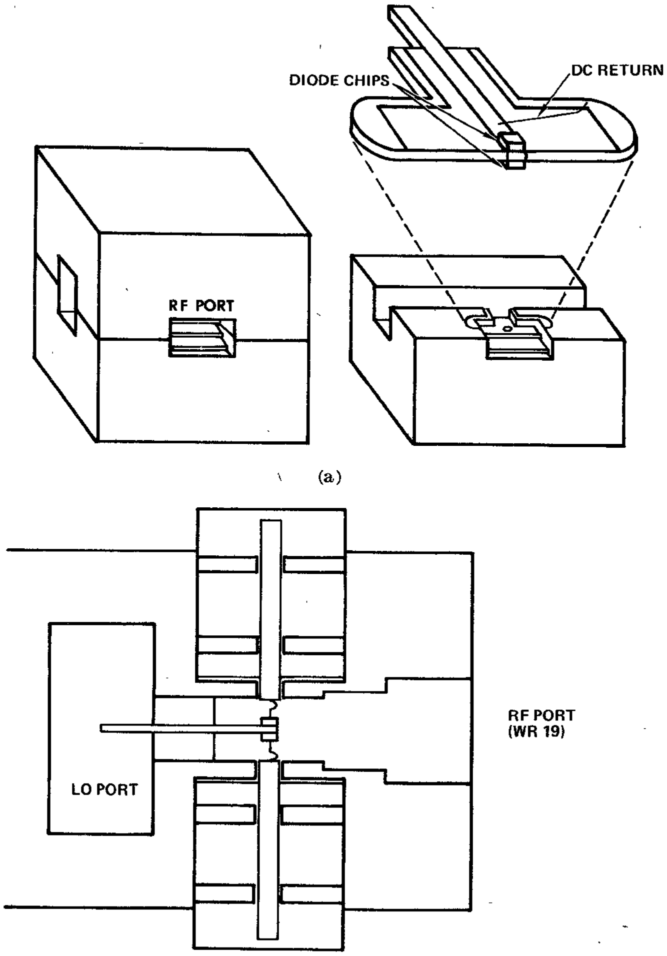

Fig. 1. Mixer configuration. (a) Suspended substrate supports diodes and serves as a probe in the LO waveguide. (b) IF filter cartridges with whiskers are pressed in to contact diode chips.

with the diode junction capacitance at band center. Coupling to the LO is achieved by extending the strip transmission line 0.047 in through the LO waveguide broadwall, forming a probe transition [5], [6]. A sliding short circuit behind the probe is initially adjusted for optimum performance and then fixed in place. The IF output from each diode passes through a low-pass filter and is combined in an IF hybrid transformer. DC bias is applied separately to each diode to obtain optimum performance.

The mixer mount is a split cube 0.75 in on a side. The dielectric (5-mil-thick epoxy-fiberglass) supporting the diodes is positioned in recesses milled in the mount which locate the probe depth and the position of the diode chips. Cartridges containing the low-pass filters and contacting whiskers are pressed into the mount until contact with the diodes is made as indicated by observing the I–V characteristic.

Mixer LO-to-RF isolation and LO AM-noise suppression, functions of the impedance matching of the two diodes, were optimized by adjusting the bias to each diode while monitoring the swept-frequency LO-to-RF port isolation response. An isolation of 25 dB or greater was achieved over 85 percent of the band with a minimum value of 23 dB occurring at 58 GHz.

Plots of RF and LO port VSWR are shown in Fig. 2. Wide variations in LO port VSWR are due to the sliding short behind the probe. VSWR was minimized at the low end of the band where the available LO power was at a minimum.

The mixer conversion loss and noise figure are shown in Fig. 3 for an LO power of 5 mW obtained from available klystrons up to

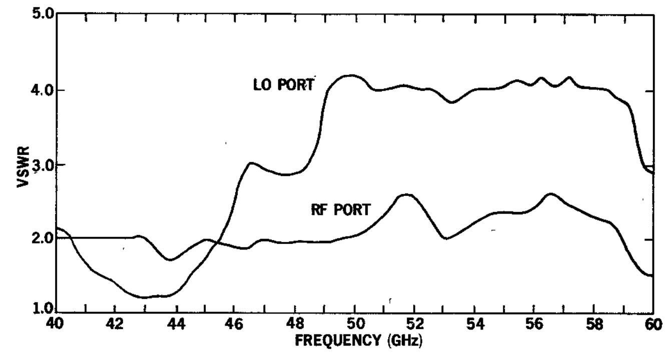

Fig. 2. RF and LO port VSWR as a function of frequency.

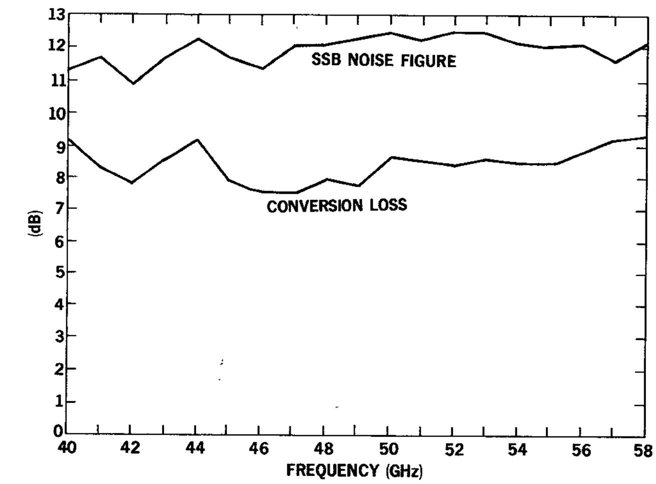

Fig. 3. Conversion loss and noise figure as a function of frequency.

58 GHz. Uncertainty in the conversion loss measurement is estimated to be less than 1 dB. Using Barber's curves [7], for a pulse duty ratio of about 25 percent, the conversion loss would be about 6 dB, including R_s loss. IF transformer loss is 0.25 dB. Mismatch losses are about 1.2 dB. An estimate of 1 dB is made for the loss at the sum frequency. Thus the anticipated conversion loss of 8.5 dB is confirmed by the measured results. Noise figure was measured using the Y-factor method with a gas tube noise source. The IF amplifier has a 2.6-dB noise figure and a 5–500-MHz bandwidth.

The feasibility of a full-waveguide bandwidth-balanced mixer at 40–60 GHz using unencapsulated Schottky-barrier diodes has been demonstrated. The measured conversion loss is 8.5 dB $\pm$ 1.0 dB from 40–58 GHz.

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