SUBHARMONICALLY PUMPED MILLIMETER-WAVE MIXERS BUILT WITH NOTCH-FRONT AND BEAM-LEAD DIODES

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Abstract

Low noise and wide tunable bandwidth have been achieved in two-diode subharmonically-pumped hybrid integrated downconverters. A single-sideband mixer noise figure of 5 dB was measured at 98 GHz with Schottky-barrier diodes of a unique chip design, "notch-front diodes", mounted in a two-diode downconverter. A second circuit has been developed with a tunable bandwidth of 66-110 GHz. Over this frequency range, conversion loss of 5-9 dB and receiver noise figure of 10-14 dB, including an IF noise figure of 4 dB, was measured in a circuit using commercial beam-lead diodes.

Introduction

The two-diode subharmonically-pumped hybrid integrated downconverter[1] has demonstrated low noise figure and conversion loss[2], broad bandwidth, and AM local oscillator noise suppression[3] at millimeter wavelengths. We report improved circuits which have achieved almost twice the tunable bandwidth and 3 dB lower mixer noise figure in comparison with earlier results.

An improved local oscillator input section was incorporated in the two-diode downconverter, and it increased the tunable RF bandwidth to the full range of WR-10 waveguide while maintaining all the desirable features of the earlier circuit. Commercially available beam-lead diodes were mounted in this downconverter, and single-sideband receiver noise figure of 10-14 dB, including the contribution from a 4 dB IF noise figure, was measured over 66-110 GHz.

The semiconductor devices which are used in this downconverter must be matched to the surrounding circuit to obtain optimum electrical performance. Matching is more readily achieved if the junction can be incorporated into the circuit with minimum parasitic reactance. A method is described in this paper which overcomes previous difficulties in reducing undesired parasitics by use of a novel chip geometry which we refer to as the notch-front diode. Notch-front diodes can be readily soldered to millimeter-wave thin film circuits. The resulting diode mount combines the best properties of the poly-isolated beam-lead structure[4], the recently described notch-back diode mount[5], as well as the frequently used Sharpless Wafer mount[6]. The notch-front diodes are particularly suited for use in conventional and subharmonically pumped millimeter-wave mixers because the reduced parasitic capacitance results in a better switching waveform and because the smaller chip size has a lower RF series resistance than conventional millimeter-wave diode structures. Notch-front diodes were mounted in the two-diode downconverter circuit reported in Reference 2 and a single-sideband mixer noise figure of 5 dB was obtained at 98 GHz. This value is comparable to the best results of fundamental mixers in this frequency range[7] and represents a 3 dB improvement over the best mixer noise figure obtained in this two-diode downconverter with beam-lead diodes. In addition, there was a 10 dB reduction in the local oscillator power required to achieve minimum receiver noise figure due to the lower parasitic reactances of these diodes.

These two-diode downconverters look promising for scaling to other frequencies and could be useful in applications such as microwave and millimeter-wave communications, plasma diagnostics and radio astronomy.

Circuit Description

A detailed view of the stripline conductor pattern is shown in Fig. 1, and a photograph of the mixer with the cover removed is presented in Fig. 2. The circuit consists of a signal waveguide input section, a waveguide to stripline transition, a stripline conductor pattern including mounting pads for a pair of Schottky barrier diodes and two low-pass filters, and a transition from the pump waveguide to the stripline. The signal waveguide to stripline transition, illustrated in Fig. 3, can be tuned by adjusting the waveguide backshort and the H-plane waveguide short such that the downconverter can be operated either as a single-sideband (SSB) or as a double-sideband (DSB) mixer.

Two low-pass filters are needed to separate the signal frequency ω_s, the pump frequency $\omega_p = 1/2(\omega_s-\omega_{if})$, and the intermediate frequency ω_{if}. The filter which is adjacent to the diode pair has a cutoff frequency of 59 GHz in order to reject the signal (66 to 110 GHz) while transmitting the pump (32.8 to 54.3 GHz) and the IF (1.4 GHz). The second low-pass filter rejects the pump and transmits the IF. The thin-film chromium-gold conductor pattern is fabricated on fused quartz substrates using standard photolithographic processing techniques.

The input signal is coupled to a pair of Schottky barrier diodes which are shunt mounted on the stripline with opposite polarities. The notch-front diodes, which were soldered to the stripline conductor, had a zero-bias junction capacitance of about 7 fF and a series resistance R_s of about 9.5 ohms. The corresponding zero-bias cutoff frequency is approximately 2400 GHz. The commercial diodes used in the wideband circuit were beam-lead devices with $R_s \simeq 3.5$ ohms and a total capacitance of approximately 70 fF. These diodes were thermocompression bonded to the thin-film circuit.

NOTCH-FRONT DIODES

In order to mount the diode chip on a substrate, it is necessary to fabricate an ohmic contact and an array of junctions on adjacent sides of a chip as shown in Figure 4. A silicon dioxide layer with a thickness of 5000 Å is first deposited on the epitaxial layer side of a gallium arsenide slice. An array of notches is then cut into a GaAs slice with a diamond saw blade. The slice has a thickness of approximately 300 µm and the notches are cut to a depth of 100 µm. An ohmic contact is formed in the notches by electroplating Sn-Ni, Ni and Au into the notches and by subsequently alloying the slice at a temperature of 400°C for 60 seconds. The notches are filled with photoresist and an array of Schottky barrier diodes is fabricated on the front of the slice by a sequence of processing steps involving masking with photoresist, plasma etching of holes into an SiO_2 layer which covers the top surface of the slice, and electroplating of platinum and gold on the exposed GaAs surface in the hole areas. A pulse plating technique developed by Burrus[8] is used to obtain uniform deposition of the metal films in all the hole areas. A detailed description of the junction formation steps is given in a separate paper[9].

Figure 5 is a scanning electron micrograph of the slice after fabricating the notches with ohmic contacts and the junctions on top of the slice. The width of the notches is about 70 µm. While some overplating of gold is visible around some parts of the top periphery of each chip, this overplating does not affect the performance of the final device. The individual junctions on the top surface of the slice have a diameter of 2 µm and a center-to-center spacing of 5 µm. This randomly contactable structure (honeycomb diode) solves the lead attachment problem as described by Young and Irvin[10]. Individual diode chips are fabricated by mounting the notched slice with the top surface down on a glass slide with wax and by back-lapping the slice to a thickness which is smaller than the depth of the notch. The chips are separated by dissolving the wax in a solvent. An individual diode chip after the backlapping of the slice is illustrated in Figure 4. A typical length of the side of the chip is 75 µm. The minimum length is determined by the depth of the damage created by the diamond saw blade which is about 10 µm.

Millimeter-wave circuits are made by mounting notch-front diodes on the conductor pattern of a strip-line substrate. The chip is soldered on one side of a gap in the conductor, and contact is made to a diode on the chip by a pointed spring wire soldered to the other side of the gap. The wire used for diode contact is 12 µm diameter Phosphor Bronze A. A short length of the wire is soldered to a heavier pin so that it can be handled, and a point is made electrolytically. A spring with the shape shown in Fig. 6 is bent in a micromanipulator, and the wire is then stress relieved for one hour at 218°C in a forming gas atmosphere. The substrate with the mounted chip is clamped in the mixer block before the diode is contacted and the IF port connection is made so that the diode dc characteristic can be monitored during assembly. The assembly is performed with micromanipulators under a stereo microscope.

Performance

The measured conversion loss and SSB receiver noise figure, including the contribution from a 3.3 dB IF noise figure, are shown in Fig. 7 for the mixer using the notch-front diodes. Conversion loss, L, was determined by direct power measurements at the signal and intermediate frequencies, and receiver noise figure, F_{tot}, was measured by the Y-factor method with loads at room and liquid nitrogen temperatures. These measurements were checked at several frequencies by determining noise figure with the small signal method[11] and conversion loss from the noise power data for hot and cold loads. The mixer noise figure, F_M, was calculated from the relation

$$F_{tot} = F_M + L(F_{if} - 1)$$

where F_{if} is the noise figure of the IF system.

The best calculated SSB mixer noise figure was 4.6 dB obtained at a signal frequency of 98 GHz. The corresponding 390 K single-sideband mixer noise temperature is comparable to that of the best conventional room temperature mixers in this frequency range, 420 K at 85 GHz and 500 K at 115 GHz[7]. The instantaneous IF bandwidth was measured with the mixer tuned for optimum noise figure, and the conversion loss was found to vary less than 0.5 dB over a 600 MHz frequency range centered at 1.4 GHz. Minimum receiver noise figure was obtained with about +8 dBm of pump power. The low frequency limit for the operation of this mixer was set by the cut-off frequency of the pump waveguide.

A summary of the mid-band performance of the down-converter and a comparison with the results obtained using the best available beam-leaded diodes[2,12] in the same circuit is shown in Table I.

TABLE I

PERFORMANCE OF TWO-DIODE STRIPLINE RECEIVER

Signal Frequency 98 GHz	Notch-Front Diodes	Beam-Lead Diodes
Mixer Noise Figure F_M Single-Sideband	4.6 dB	8 dB
Mixer Noise Temperature T_M Single-Sideband	390 K	1600 K
Conversion Loss	7.4 dB	8 dB
Pump Power at 48.3 GHz	8 dBm	18 dBm

The performance of the wideband mixer using typical commercial beam-lead diodes is given in Fig. 8. The tunable bandwidth of this mixer exceeds the recommended operating range of the WR-10 signal waveguide. The pump power used with these diodes was about +14 to +18 dBm.

Summary

A new type of Schottky barrier diode chip, the notch-front diode, has been developed for use in stripline circuits. This chip has an ohmic contact on its four side faces, which facilitates soldering the chip to the conductor pattern of the stripline. A mounting technique has been devised in which the chip is soldered on one side of a gap in the stripline conductor, and contact is made to a diode with a pointed wire spring soldered on the other side of the gap. The notch-front chip mounted in this way has considerably lower parasitic reactances than the beam-lead diodes usually used in stripline circuits. When notch-front chips were mounted in a 98 GHz millimeter-wave downconverter, a 3 dB improvement in mixer noise figure was obtained in comparison with beam-lead diodes due to the lower parasitic reactance.

Secondly, it has been shown that the tunable bandwidth of these mixers can be improved to include an entire waveguide band. This result was demonstrated in a mixer using commercial beam-lead diodes, but the use of "notch-front" diodes in this broadband circuit should combine low noise performance with wide tunable bandwidth.

These mixers can be readily scaled to other frequency bands and should prove useful in many millimeter wave applications.

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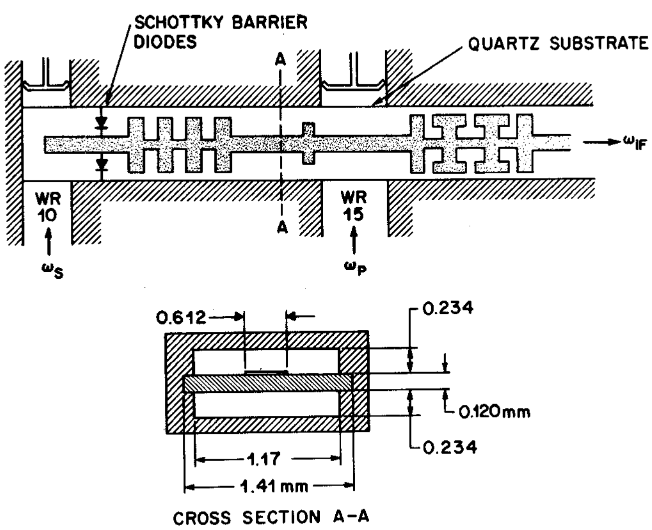

Fig. 1-Top view and cross-sectional view of the strip-line circuit with signal and pump waveguide input ports. The pump waveguide was WR-15 for the mixer using the notch-front diodes and WR-19 for the wideband mixer.

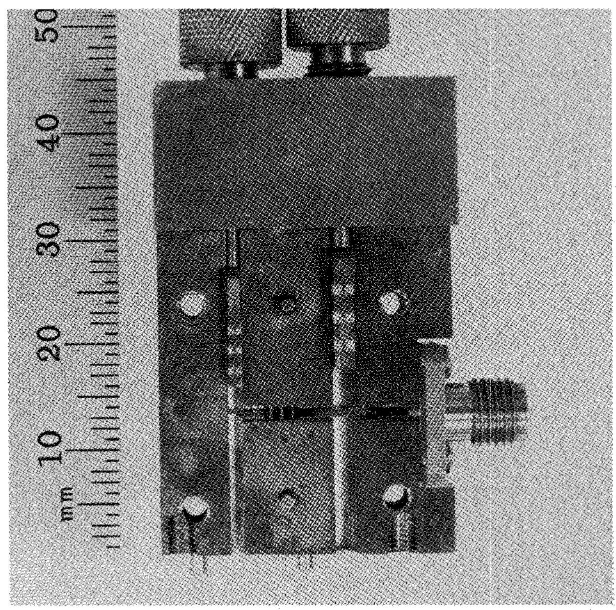

Fig. 2-Photograph of the low noise mixer. The top cover of the housing is removed to show the conductor pattern on the quartz substrate.

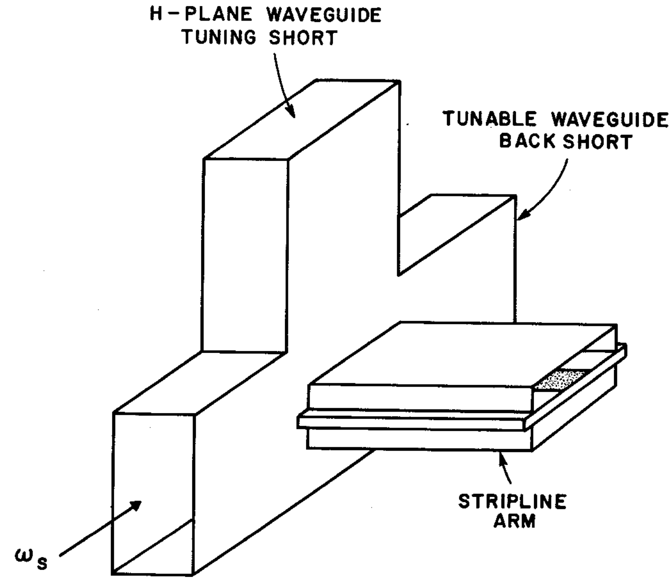

Fig. 3-Transition from signal waveguide to stripline circuit with a tunable waveguide backshort and an H-plane tunable short for matching the signal and rejecting the image frequency.

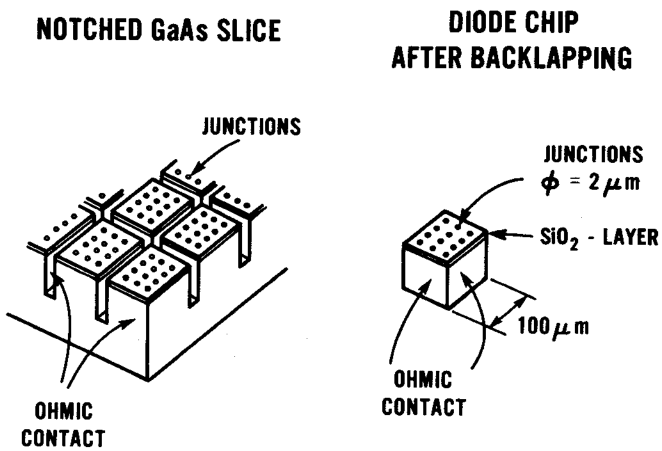

Fig. 4-Schematic view of notched GaAs slice and diode chip after backlapping.

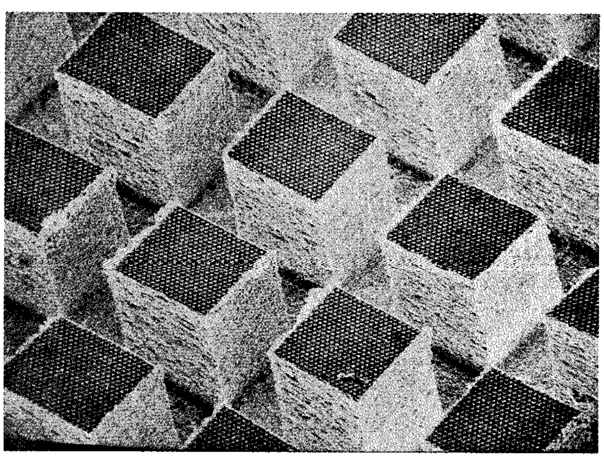

Fig. 5-Scanning electron micrograph of notch-front diodes with a dice size of 75 µm × 80 µm and a notched depth of 100 µm. The junction diameter is 2 µm with a center-to-center spacing of 5µm.

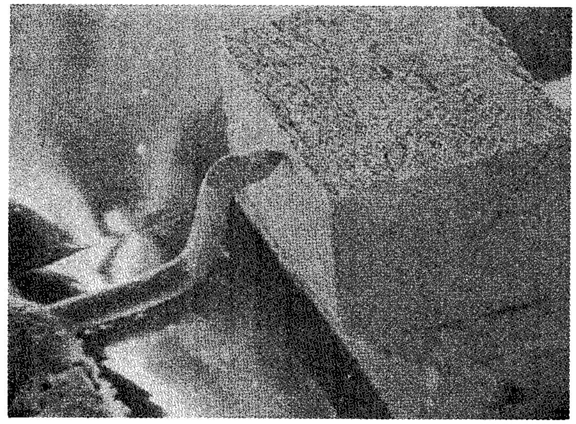

Fig. 6-Scanning electron micrograph of a notch-front chip mounted on a stripline circuit. The chip dimensions are 100 µm × 100 µm × 125 µm, and the gap in the stripline conductor is 100 µm.

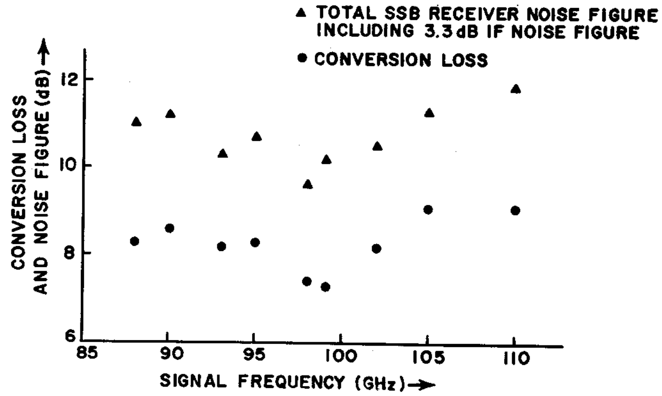

Fig. 7-Total SSB receiver noise figure, including the contribution from a 3.3 dB IF noise figure, and conversion loss of the notch-front diode mixer as a function of frequency from 85 to 110 GHz. The data points are obtained with the circuit adjusted for optimum receiver noise figure at each frequency.

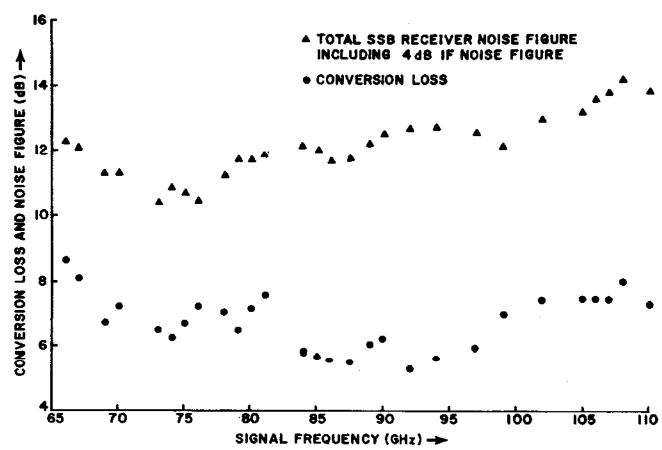

Fig. 8-Total SSB receiver noise figure, including the contribution from a 4 dB IF noise figure, and conversion loss of the wideband mixer using commercial diodes as a function of frequency. The data points are obtained with the circuit adjusted for optimum receiver noise figure at each frequency.