measurements. This is due to the neglect of ohmic losses in the calculations. The difficulty can be overcome, however, if the losses are taken into account according to the guidelines given in [3].

VI. Conclusions

A fin-line equivalent has been developed, which is thought to fill the gap for a first-order design theory. This method reduces boundary value problems in complex fin-line structures to the problem of matching the TE_{m0} modes between two sets of equivalent rectangular waveguides. Its usefulness has been checked by applying it to the analysis of fin-line discontinuities and of a bandpass filter.

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An X-Band Balanced Fin-Line Mixer

GÜNTHER BEGEMANN

***Abstract*—The fin-line technique has been used in a balanced 9–11-GHz mixer with a 70-MHz intermediate frequency. The mixer without an IF amplifier has an available conversion loss of less than 5 dB with a 3.8-dB minimum and a SSB noise figure of less than 6.9 dB with a 5.3-dB minimum. The mixer is tunable by variable shorts. It is possible to scale the device to millimeter-wave frequencies.**

I. Introduction

THIS PAPER describes the design and performance of a microwave integrated-circuit (MIC) balanced mixer that covers the bandwidth of 2 GHz within the X band with available conversion losses of less than 5 dB and a noise figure of less than 6.9 dB. Not included is the noise contribution from the IF amplifier. The mixer operates with an IF of 70 MHz, but the device is able to handle higher IF's up to some gigahertz. For this purpose, the low-pass filter coupling out the intermediate frequency must have a suitable cutoff frequency.

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In the circuit considered here, a fin-line technique [1] has been used to realize a mixer which is capable to work well up to millimeter-wave frequencies. To this end the mixer is equipped with connections of rectangular waveguides both at the signal and the local oscillator input.

Because the fundamental mode of a fin-line (H_{10} mode) is the same as the one of a rectangular waveguide, transitions between these two guides are easy to handle and have a very small insertion loss and a VSWR over the entire waveguide bands. Parasitic radiation which often is a problem connected with planar waveguides especially at higher frequencies can be avoided. So the fin-line has very low losses. Moreover, it offers the same possibilities of integration as other planar circuits.

The most essential part of the mixer is a planar magic T completely integrated in a rectangular waveguide. The magic T proved itself as a rather broad-band and low-loss device. The purpose of the magic T is twofold. First, it distributes the signal and local oscillator voltages with their proper phase relationships to the two nonlinear elements, and, second, it blocks the local oscillator input from the signal frequency input and vice versa.

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A main feature of the mixer is that it is tunable by variable shorts. Thus tuning of the signal input impedance is performed with low loss and as fast and accurate as in conventional waveguide circuitry.

Although the fin-line seems to be advantageous, especially for millimeter-wave applications, we have designed the mixer for a signal center frequency of 10 GHz because at this frequency measurements can be made exactly.

II. A Fin-Line Magic T

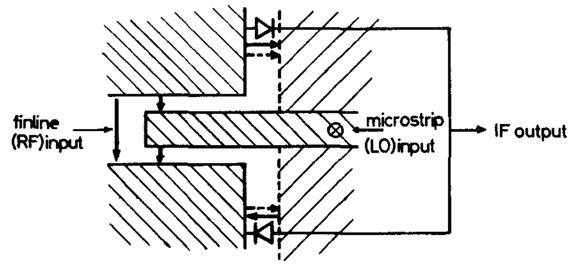
To realize balanced mixers, 90° or 180° hybrids are required. To do this with planar circuits, one can use branchline couplers, ring hybrids, parallel-coupled-line couplers, combinations of orthogonal transmission lines like slot lines and coplanar lines, or magic T's. There are several papers which deal with such mixers [2]–[4], and excellent results have been reported.

A hybrid junction similar to the one treated here is known from the literature [5]. The junction presented in [5] is but a pure planar device. We have designed a magic T of a fin-line–microstrip hybrid junction, as shown in Fig. 1. The fin-line magic T acts as follows. A wave incident from the left on the slot of a fin-line (its electric field is represented by solid arrows) excites two waves first guided by the slots between the microstrip antenna and the top and the bottom of the fin-line slot. These waves provide antisymmetric antiphase excitation of the cross arms which act as output ports. In case of perfect geometrical symmetry there occurs no excitation of the waves on the microstripline. A wave incident from the right on the microstripline (its electric field is represented by dashed arrows) excites symmetric inphase waves on the cross arms. The protruding part of the microstrip, i.e., the part of the microstrip without back-side metallization, acts as an antenna. Its optimum length, in order to match the microstrip input, was determined experimentally at 10 GHz. Typical dimensions are given in Fig. 2 but depend on the impedance level of the device. Data that is generally valid cannot be given because we did not execute theoretical investigations.

At nonlinear elements placed in the cross arms, as shown in Fig. 1, the incident waves beat once in phase and once in antiphase. If the microstrip side of the hybrid is used as a local oscillator (LO) input and the fin-line side as a signal (RF) input in a common IF output, the LO currents cancel and the IF currents are inphase. So this arrangement is capable of being used as a balanced mixer.

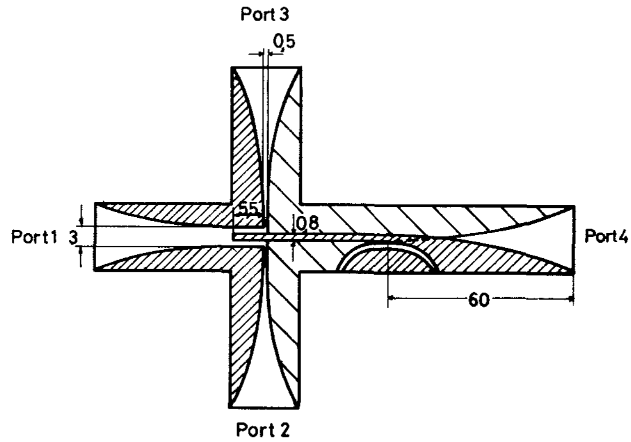
Because the cross arms are series-connected referred to the fin-line input but parallel-connected referred to the microstrip input, their impedance must be chosen to be half the impedance of the fin-line input and twice that of the microstrip input. Methods for calculating fin-line impedances are available from the literature [6], [7].

Fig. 2 essentially shows the planar structure of the complete magic T with its waveguide ports as used for optimization. One has to imagine this planar structure as being mounted parallel to the narrow sides of two cross-



Metallization on the front side of the substrate
Metallization on the back side of the substrate

Fig. 1. The fin-line magic T.



Metallization on the back side of the substrate
Metallization on the front side of the substrate

Fig. 2. Substrate of the complete fin-line magic T with its waveguide input and output ports; typical dimensions are in millimeters; thickness of the substrate is 0.254 mm; permittivity is 2.22 (RT/Duroid 5880).

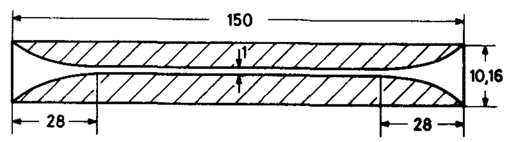


Fig. 3. Two fin-line tapers in a series connection; dimensions are in millimeters as used for the measured results of Fig. 4.

connected rectangular waveguides. Ports 1 and 4 serve as input ports, and ports 2 and 3 are used as output ports.

Port 1 is constructed with a fin-line taper. Such tapers are uncritical in their dimensions. Measurements at two tapers in a series connection, arranged as in Fig. 3 and printed on a 0.254-mm teflon substrate (RT/Duroid 5880, $\epsilon_r = 2.22$) which we used throughout the development of the mixer, showed a typical insertion loss of about 0.2 dB and a VSWR of about 1.2 over the entire X band, as shown in Fig. 4. Included are the losses of the cylindrical part of the device between the two tapers.

The transition at port 4 contains a fin-line taper, a short section of an antipodal fin-line [6], and a microstripline. An additional metallization prevents the metal-free space below the taper from resonating in the considered frequency band. Measurements at two of such transitions as shown in Fig. 5 yielded a typical insertion loss of less

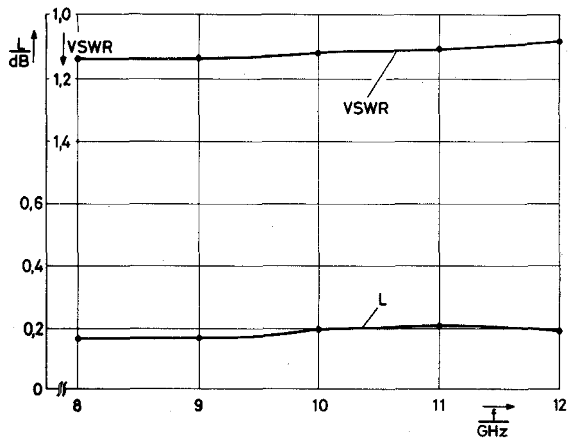


Fig. 4. VSWR and insertion loss L of two fin-line tapers in a series connection; dimensions of the substrate are as shown in Fig. 3.

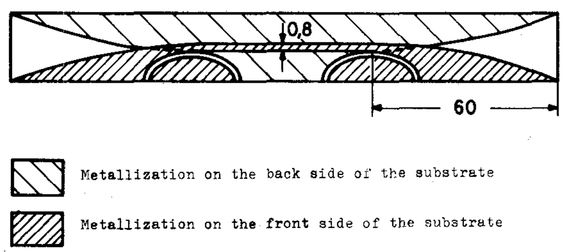


Fig. 5. Two transitions from a rectangular waveguide to a microstrip in a series connection; dimensions are in millimeters as used for the measured results of Fig. 6.

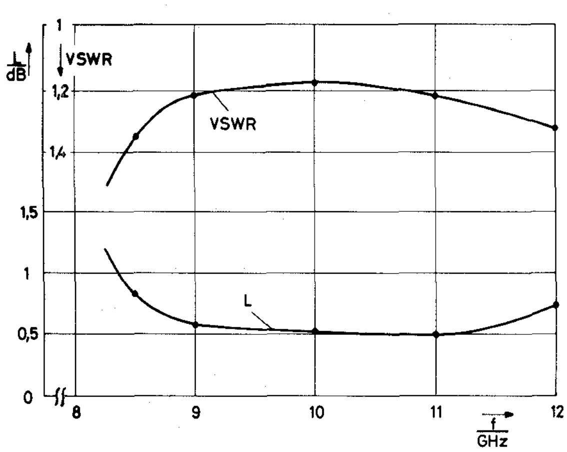
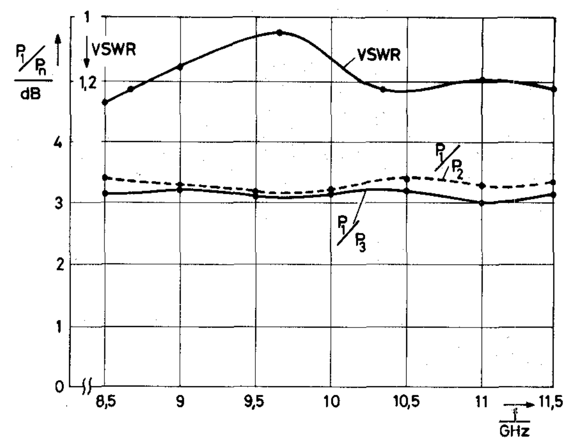
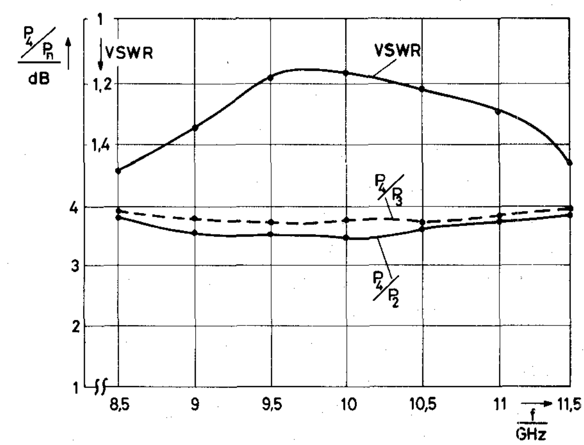


Fig. 6. VSWR and insertion loss L of two transitions from a rectangular waveguide to a microstrip; dimensions of the substrate are as shown in Fig. 5.

than 0.8 dB and a VSWR of less than 1.35 within the 8.5–12-GHz band, as shown in Fig. 6. All the measurements showed that a transition from a rectangular waveguide to a microstrip is more difficult to design than the simpler transition from a rectangular waveguide to a fin-line. Thus the useable bandwidth of a device using both types of transition mainly is determined by the transition from a rectangular waveguide to a microstrip. In general, the insertion loss and the VSWR of both the transitions increase with an increasing ratio of the waveguide input and the fin-line or microstrip output impedances and with a decreasing length of the transition.



(a)



(b)

Fig. 7. VSWR at the input ports and ratios of the input and output ports powers measured at the fin-line magic T of Fig. 2. (a) Input at port 1. (b) Input at port 4. $P_n \cdots$ power at port n.

Measurements at the hybrid junction of Fig. 2 have yielded a maximum power imbalance of 0.3 dB and a maximum phase imbalance of 2° between the output ports 2 and 3. That was true for waves incident at port 1 as well as at port 4. The isolation between port 1 and port 4 and vice versa was 35-dB minimum with a 40-dB average. These results critically depend on the symmetry of the device. Fig. 7(a) shows the maximum insertion loss between port 1 and one of the output ports to be 0.4 dB with a 0.3-dB average within the 8.5–11.5-GHz band. The VSWR was better than 1.27. As Fig. 7(b) shows, the insertion loss between port 4 and one of the output ports was slightly higher due to a higher reflection coefficient; a 0.9-dB maximum with a 0.7-dB average has been observed within the same frequency band. The VSWR was less than 1.5.

III. The Complete Mixer Configuration

The complete mixer is shown in Fig. 8 [8]. The LO power is fed to the mixer from a rectangular waveguide via the transition-1 and a 50-Ω microstripline. A metallization-2 is added as in the case of the fin-line magic T. The RF power input is constructed of a fin-line taper-3. The

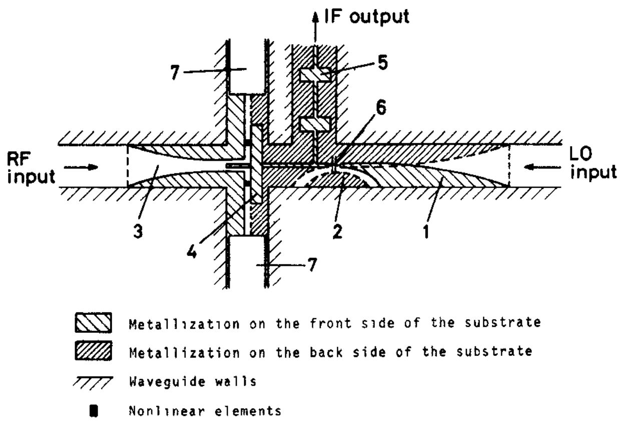


Fig. 8. The complete mixer configuration: 1 is the waveguide to microstrip transition, 2 is the additional metallization, 3 is the fin-line taper, 4 is the microstrip stub, 5 is the low-pass filter, 6 is the block capacitor, and 7 is the variable shorts.

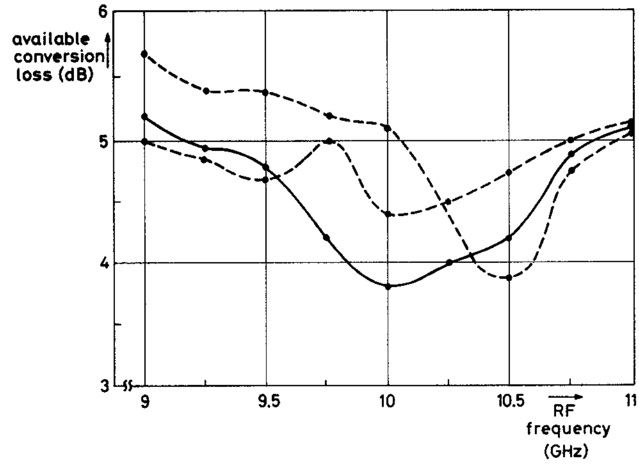


Fig. 9. Measured available conversion loss as a function of the RF frequency with a fixed LO power of 12 dBm and an intermediate frequency of 70 MHz. Solid line is the mixer optimized at 10 GHz. Dashed lines are the mixer optimized at 9.5 and 10.5 GHz, respectively.

impedance of the fin-line is 200 Ω such that it is matched to the 100-Ω cross arms.

Because the ratio of the microstrip to the cross arms and fin-line input impedances must be one to two to four, one is in a way forced to choose the impedance level as done here. If the microstrip impedance is chosen less than 50 Ω on the one hand, matching of this line to the waveguide input becomes more difficult; on the other hand, the cross-arms impedances have to be less than 100 Ω which is difficult to realize in a fin-line technique. On the other hand, a microstrip impedance of more than 50 Ω would require cross-arms impedances of more than 100 Ω which makes matching of the diodes more difficult. So the impedance level chosen here is a compromise.

The microstripline carrying the LO power is simultaneously used as the IF output. To do this, the nonlinear elements are connected with the microstrip by stubs-4 terminated in an open-circuit. Concerning the LO propagating on the microstripline, the stubs act as open-circuits and the LO energy gets to the nonlinear elements by way of the magic T and the cross arms. The nonlinear elements are soldered at the middle of the stubs such that one of the two connecting contacts is grounded at the RF and LO frequencies. The hot point is on the other side of the slot. The impedances of the stubs were chosen to be about 15 Ω in order to achieve a considerably broad-band resonance behavior.

A five-section conventional microstrip low-pass filter-5 acts as a diplexer between the LO and IF. The passband insertion loss of the filter which has a cutoff frequency of 3 GHz is less than 1 dB. The RF and LO isolation is better than 35 dB. An 8.2-pF capacitor-6 which blocks the IF from the LO input is connected in series with the microstrip. A remarkable advantage of the mixer is that it is tunable by variable shorts-7 contacting at the metallized substrate. So it is easy to match the RF input and to minimize the conversion loss for different LO power levels over a considerable wide frequency band without a laborious variation of the whole mixer configuration. After tuning, the shorts can be fixed by bridging the slots of the cross arms.

The mixer was printed on a 0.254-mm teflon substrate (RT/Duroid 5880). GaAs Schottky barrier diodes[1] with a typical series resistance of 1.7 Ω, a junction capacitance of 0.4 pF, an ideality factor of 1.06, and Si beam-lead Schottky barrier diodes[2] were used as nonlinear elements. A conventional X-band waveguide served to hold the planar structure.

IV. Mixer Performance

In order to measure the conversion loss, the mixer was fed with an RF input power directly measured at the mixer input and was pumped with different LO power levels. The IF output power was measured directly at the IF output with a selective microvoltmeter. The difference of the RF input and the IF output powers gives the conversion loss L. With the IF output reflection coefficient r_{ZF} directly measured with a network analyzer, the available conversion loss L_A results in

$$L_A = L(1-|r_{ZF}|^2).$$

Available conversion loss data for the mixer is presented in Fig. 9 for a fixed LO power of 12 dBm. For these measurements, we used the GaAs diodes. The Si diodes gave slightly worse results. When the shorts were fixed such that the mixer was optimized at an RF frequency of 10 GHz, the mixer had a minimum conversion loss of 3.8 dB (solid line). When the mixer was

[1] 1SS11 of NEC.
[2] HP 5082-2264 of Hewlett-Packard.

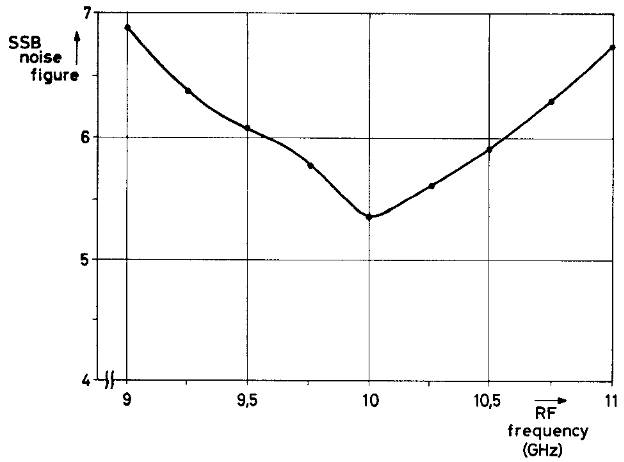


Fig. 10. Measured SSB noise figure as a function of the RF frequency with a fixed LO power of 12 dBm and an intermediate frequency of 70 MHz.

optimized at other frequencies (dashed lines), the overall behavior was slightly worse but better at specified frequencies. The RF VSWR was better than 1.3 in the 9–11-GHz band. The LO VSWR was less than 4.0 which can be improved by properly matching the LO input. The mixer output impedance was about 50 Ω. The LO–RF isolation was measured to be between 25 and 28 dB.

In order to determine the mixer's SSB noise figure, the DSB noise figure of the mixer connected with an IF amplifier (NF = 2 dB) and the upper- and lower-sideband conversion of the mixer itself were measured separately. There was no external IF matching used, but the mismatch between the mixer and IF amplifier was considered. The maximum difference between the upper- and lower-sideband conversion loss was about 0.6 dB. The results calculated from the measured values are presented in Fig. 10, and they show the SSB noise figure of the mixer itself to be less than 6.9 dB over the 9–11-GHz band when the mixer was optimized at an RF center frequency of 10 GHz.

V. Conclusions

The features of a balanced fin-line mixer working at the *X* band have been demonstrated. The main part of the mixer consists of a planar circuit. A waveguide simultaneously serves as a holder and avoids radiation from the planar structure. So the mixer has conversion losses and a noise figure comparable to waveguide mixers but the advantage of a simpler construction. Low-loss variable shorts as used in a waveguide technique have proven to be excellent tuning elements. Thus the mixer profits by the advantages of MIC and conventional waveguide technology. Measurements have been executed at the *X* band, but it is possible to scale the device to millimeter-wave frequencies.

Acknowledgment

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