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A Planar Quasi-Optical Mixer Using a Folded-Slot Antenna

Stephen V. Robertson, Linda P. B. Katehi, and Gabriel M. Rebeiz

***Abstract*—A quasioptical mixer using only planar structures such as coplanar-waveguide and slotline is presented. The mixer, which can be scaled for millimeter-wave applications and placed on a substrate lens, uses orthogonal modes in a folded-slot antenna to achieve intrinsic RF/LO isolation without RF filtering or subharmonic pumping. The folded-slot balanced mixer was fabricated on RT/Duriod and obtained a minimum isotropic conversion loss of 1.2 dB at 11.6 GHz. Numerical integration of full two-dimensional antenna patterns yielded an antenna directivity of 7 dB, corresponding to a single side-band (SSB) mixer conversion loss of 8.2 dB. The mixer demonstrated −18 dB RF/IF isolation and −30 dB LO/IF isolation.**

I. Introduction

Planar circuit designs are advantageous for producing millimeter-wave integrated circuits because they can be easily fabricated using monolithic techniques. Uniplanar circuit structures such as coplanar-waveguide (CPW) and slotline are especially useful since they eliminate the need for via holes or backside metallization and can be integrated with solid-state devices on a single surface [1]. In the past, planar microwave and millimeter-wave receivers have employed quasioptical techniques to achieve compact size and reduced transmission line loss [2]–[4]. Also, planar quasioptical receivers have exploited symmetry to realize balanced mixers [5].

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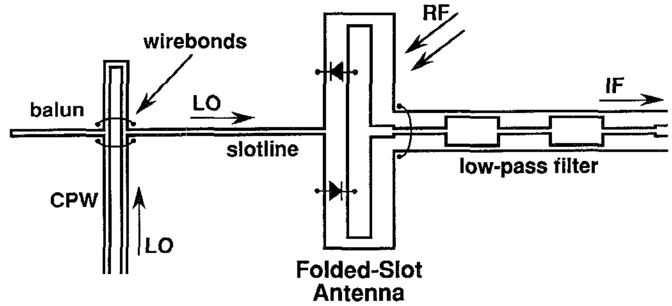

Fig. 1. Layout of the folded-slot balanced mixer circuit (reprinted from the *23rd Euro. Microwave Conf Dig.*).

This paper explores the realization of a quasioptical mixer with uniplanar structures. First, the folded-slot antenna is investigated as a planar quasioptical mixing element. Then, slotline and CPW structures are used to implement the LO pumping network and the low-pass IF filter. In the circuit configuration of Fig. 1, diodes are mounted in the slots of the antenna to provide mixing between the received RF and injected LO signals. The mixer achieves balanced mixing with good conversion loss and high port-to-port isolation.

II. Folded-Slot Antenna

The development of the folded-slot antenna was based on previously published work on coplanar-waveguide antennas [4]–[7] and was first proposed as a microshield line antenna by Rexberg *et al.* [8]. Two main characteristics of the folded-slot antenna make it especially useful for a quasioptical mixing application: 1) a planar geometry, and 2) the ability to support two orthogonal resonant modes.

Theoretical analysis of the antenna based on an SDIE method [9] shows that the folded-slot antenna is at first resonance when the length of the slots is approximately equal to half of the guided wavelength. This resonance can exist for both a CPW feed, which excites an even mode, and a slotline feed, which excites an odd mode. Fig. 2 depicts the field distributions of both of these modes for a folded-slot antenna in the first resonance. In the even mode (CPW feed) the field distribution in the slots is similar to the current distribution on a folded dipole, and the slots radiate in phase. In the odd mode (slotline feed) the slots are excited with a 180° phase difference, and therefore do not radiate. It is possible to excite both odd and even modes simultaneously by feeding the antenna from opposite sides with a CPW and a slotline. In this case, the two modes will not couple to each other since they are orthogonal. Feeding the antenna on adjacent sides with similar feed lines (either both CPW or both slotline) achieves the same result. Alternatively, similar feeds on opposite sides of the antenna will couple to the same mode with a 180° phase difference at the two feed points. In this work, the folded-slot mixer receives the RF quasioptically in the even mode, and a slotline excites the LO in the odd mode. Thus intrinsic isolation between the two orhogonal modes serves the purpose of RF/LO isolation.

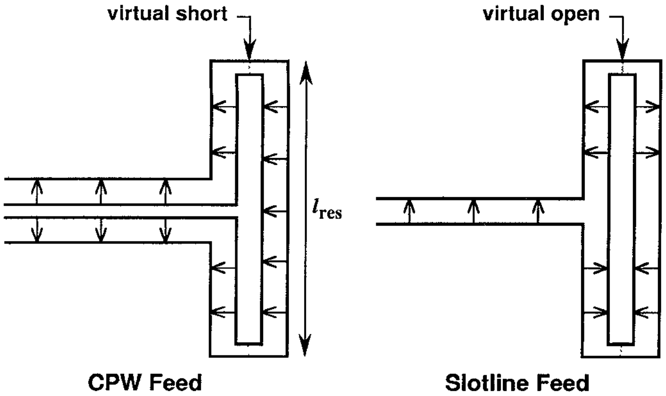

Fig. 2. Field distributions in a half wavelength folded-slot. The CPW feed excites the even (radiating) mode, and the slotline feed excites the odd (nonradiating) mode.

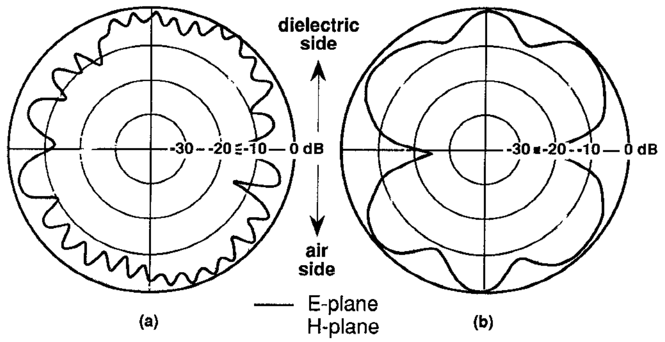

Fig. 3. Measured patterns of (a) a CPW-fed folded-slot antenna at 11.44 GHz with a 7.5-cm-diameter circular ground plane and (b) a CPW fed folded-slot antenna at 11.44 GHz with a 35 × 35-cm-square ground plane.

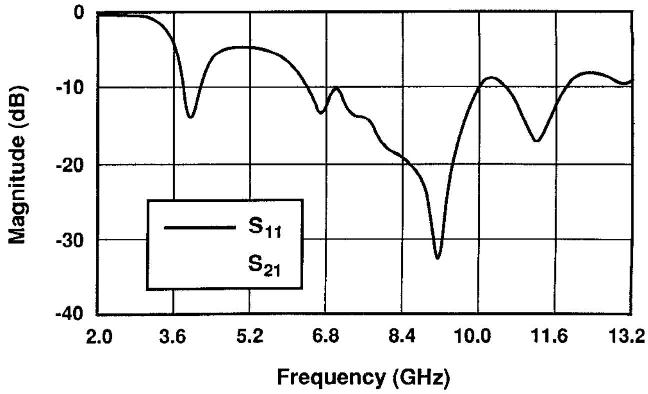

Fig. 4. Measured response of back-to-back CPW-to-slotline baluns.

The radiating properties of the folded-slot antenna are similar to those of the single slot. Theory predicts broad E-plane patterns, which implies that the size of the ground plane will affect the far field radiation. The measurements shown in Fig. 4 demonstrate that, in fact, the patterns are significantly affected by ground plane truncation. E- and H-plane patterns measured at 11.44 GHz for a CPW-fed folded-slot antenna fabricated on a very thin teflon substrate with $\varepsilon_r \cong 2.0$ are markedly different for two different size ground planes. Measurements of a folded-slot antenna with a 7.5-cm-diameter circular ground plane (Fig. 3(a)) show that ground plane truncation causes 7–8 dB dips in the pattern due to diffraction effects. As shown in Fig. 3(b), increasing the size of the ground plane eliminates the dips in the pattern, but causes a ripple. This effect has been predicted by studies on disk patch antennas [10], [11], and is in agreement with previous measurements on similar types of planar antennas [3], [4].

In order to solve the problems associated with finite ground plane dimensions, the antenna may be integrated on a substrate lens [2], [12]. The lens simulates an infinite dielectric substrate and elimates the parasitic radiation caused by surface waves. Also, with the addition of a substrate lens, the antenna radiates most of its power into the dielectric (a ratio of $\varepsilon_r^{3/2}$:1 power radiated into the dielecric versus power radiated into air), resulting in unidirectional radiation patterns.

III. Quasi-Optical Mixer

Implementation of the folded-slot mixer requires planar circuits for the LO pumping network and the IF output filter. Connections to the circuit are made with SMA type coaxial connectors. Because of the transforming properties of the transition from SMA to CPW [13], a characteristic impedance (Z_0) of 70 Ω is used for all transmission lines. In order to feed the LO into the mixer with a slotline, a transition from CPW to slotline is necessary. A 4-port balun transition [14] was selected for this purpose due to its simplicity. The balun (see Fig. 1) consists of an open-circuit quarter-wavelength CPW stub ($l_{\mathrm{cpw}} =$ 2.95 mm, $Z_{\mathrm{cpw}} = Z_0$), and a short-circuit quarter-wavelength slotline stub ($l_{\mathrm{slot}} = 3.63$ mm, $w_{\mathrm{slot}} = 100$ μm, $Z_{\mathrm{slot}} = Z_0$). The insertion loss of back-to-back baluns fabricated on a RT/Duriod substrate ($h = 1.27$ mm, $\varepsilon_r = 10.5$), including SMA-to-CPW transitions, was measured to be less than 3 dB up to 12 GHz, as shown in Fig. 4.

The IF output of the mixer couples into the even mode of the antenna [15] and is extracted by a CPW line. To prevent the RF from coupling to the CPW line, a stepped impedance low pass IF filter is used. Since this is a quasioptical circuit and the mixing occurs within the antenna itself, the IF filter should be designed so as not to disturb the RF fields. This is accomplished by using quarter-wavelength sections in the filter and presenting an open circuit to the RF fields at the IF/antenna connection. The IF filter has a 3-dB response at 6.4 GHz, and −18 dB rejection at 11 GHz.

In order to maximize the LO power available to the diodes, the folded-slot antenna used in the mixer is designed to be resonant for the 100-μm slotline feed. Results of the SDIE analysis give an antenna with a slot length l_{res} of 6 mm, a slot width of 500 μm, and a slot separation of 500 μm. The end slots are 200 μm wide.

The mixer circuit is fabricated using wet etching on a circular copper clad RT/Duroid substrate with a dielectric constant of 10.5, a diameter of 7.5 cm, and a thickness of 250 μm. The mixer diodes (Hewlett-Packard HSCH-5 320, $C_T = 0.10$ pF, $R_s = 15$ Ω) are mounted symmetrically about the slotline feed in an anti-parallel configuration (see Fig. 1). Balanced mixing occurs since the diodes receive the RF signal 180° out of phase and are pumped in phase by the LO [15].

IV. Measurements

Antenna patterns of the mixer itself (see Fig. 5) were obtained at 11.8 GHz by using the diodes as detectors. The RF patterns of the mixer are very similar to the measured patterns of the CPW fed folded-slot. Both patterns show the 8–10 dB dips caused by ground plane truncation. The directivity of the antenna on the dielectric side is estimated to be $D_{\mathrm{fs}} \cong 7$ dB by numerical integration of a full two-dimensional pattern.

The mixer conversion loss is defined as the available RF power at the antenna "terminals" divided by the measured IF power. The available RF power is given by

$$P_{\mathrm{RF}} = S_r \cdot A_{\mathrm{eff}} = \left(\frac{P_t G_t}{4\pi R^2}\right)\left(\frac{\lambda^2}{4\pi} D_{\mathrm{fs}}\right) \quad (1)$$

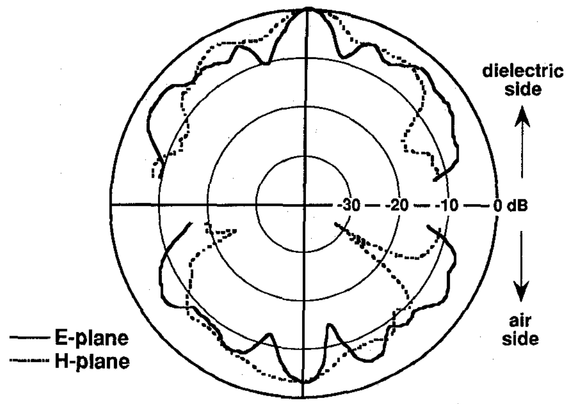

Fig. 5. Measured RF patterns of the folded-slot quasioptical mixer using the mixer diodes as detectors at 11.8 GHz.

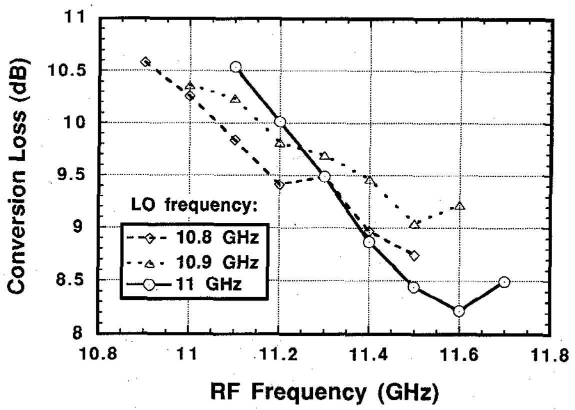

Fig. 6. Measured conversion loss of the folded-slot mixer versus LO frequency (see text for definition of conversion loss). (Reprinted from the *23rd Euro. Microwave Conf. Dig.*)

where S_r is the incident RF power density, A_{eff} is the effective aperture of the folded-slot antenna, and P_t is the RF power transmitted by a standard gain horn with gain G_t. The conversion loss of this mixer can then be found using (2)

$$L_c = \frac{P_{\text{RF}}}{P_{\text{IF}}} = \frac{P_t G_t \left(\frac{\lambda}{4\pi R}\right)^2 D_{\text{fs}}}{P_{\text{meas,IF}}/G_{\text{IF}}} \tag{2}$$

where G_{IF} is the measured gain of the IF path.

A minimum SSB conversion loss of 8.2 dB is measured for $f_{\text{RF}} = 11.6$ GHz, $f_{\text{LO}} = 11.0$ GHz, and $P_{\text{LO}} = 8$ dBm, as shown in Fig. 6. The mixer has good port-to-port isolation, with -18 dB RF/IF isolation and at least -30 dB LO/IF isolation at the point of minimum conversion loss.

The mixer can also be characterized by the *isotropic conversion loss*, which is defined as the conversion loss that would be obtained if the mixer were assumed to have an ideal isotropic radiating element [3]. The isotropic conversion loss can be calculated from (2) by setting the antenna directivity, D_{fs}, equal to one. For the folded-slot mixer the conversion loss of 8.2 dB includes the measured antenna directivity of 7 dB and corresponds to an isotropic conversion loss of 1.2 dB. This compares well to the measured isotropic conversion loss of approximately 3 dB at 10.1 GHz for a coupled-slot quasioptical receiver with a nonplanar feed structure [4].

V. Conclusion

A planar quasioptical mixer has been presented. The mixer achieves RF/LO isolation through the use of orthogonal modes in a folded-slot antenna, without RF filters or subharmonic LO. Balanced mixing is achieved with good conversion loss and high port-to-port isolation. The uniplanar design of the mixer is suitable for monolithic fabrication, which extends the circuit's usefulness into the millimeter-wave frequency range. The mixer may be integrated on a substrate lens at millimeter-wave frequencies to eliminate the problem of surface modes.

Acknowledgment

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