Planar Diode Mixers and Frequency Multipliers for Microwave and Wireless Systems

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Introduction

Wireless and other commercial applications create special needs for diode circuits. Because most such systems are manufactured in large quantities, they must be low-cost. To minimize cost, especially in monolithic circuits, the circuits must be very simple, and especially must be planar. Unfortunately, most conventional designs for doubly balanced diode mixers and frequency multipliers are nonplanar.

It is important to note that all doubly balanced mixers are realized in only two fundamental types: the ring and star configurations [1]. All ring or star mixers are fundamentally identical; the only difference between individual designs is in the baluns or hybrids used to realize the mixer. Mixer design is fundamentally balun design.

In this article we will examine a number of approaches to the design of baluns for planar diode circuits such as mixers and balanced frequency multipliers. We will also describe some of the circuits in which they have been used and show that good performance can be achieved.

Baluns and Hybrids

Diode mixers and resistive diode frequency multipliers can be very broadband. Because diodes can have very small junction capacitances (as little as 0.005 pF when necessary), the junction capacitance rarely limits bandwidth; instead, bandwidth is usually established by the embedding circuit, especially the baluns or hybrids. In the design of a diode mixer or resistive multiplier, one tries to avoid the use of a reactive matching circuits. Usually the diode is selected so that its junction capacitance is negligible, and the embedding circuit is designed to match the pumped diode's effective input or output resistance.

Most practical diode mixers and multipliers are balanced. Single-diode circuits are occasionally used in simple, low-cost applications where performance need not be high. Balanced circuits offer a number of advantages over single-diode circuits, including inherent port-to-port isolation and (in mixers) rejection of AM LO noise and certain even-order intermodulation products. These advantages depend strongly on the balance of the hybrids or baluns used in the circuit; achieving good balance in a broadband hybrid is usually difficult.

Transmission-Line Baluns

Figure 1 shows a ring mixer using a pair of wire-wound transformers as baluns. A transformer has one important advantage over a microwave balun: a mixer's IF connection can be made to the center-tap of the transformer, where both the RF and LO voltages are zero. In this way, good RF-to-IF and LO-to-IF isolation are assured. Because of the limitations in fabricating RF transformers, such mixers can be realized at frequencies up to, at most, 1 GHz. At higher frequencies one must use another type of balun.

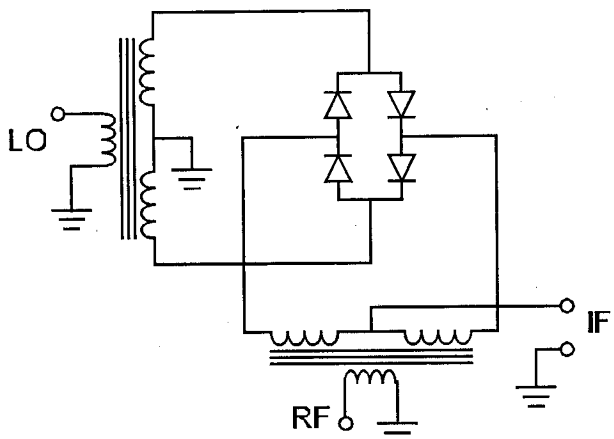

Fig. 1. A doubly balanced diode-ring mixer using transformers as baluns

One of the most commonly used microwave baluns is a simple, quarter-wavelength transmission line. Figure 2 shows such a balun. It consists of a 1/4 section of transmission line whose characteristic impedance Z_0 is chosen to act as a transformer between the source impedance Z_s and the load impedance Z_L:

$$Z_0 = (Z_s Z_L)^{0.5} \qquad (5.1)$$

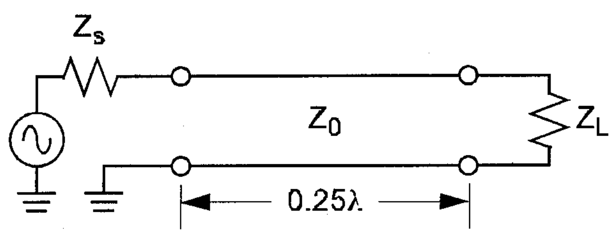

Fig. 2. A simple transmission-line balun

To account for stray capacitance between the conductors and ground, we can treat the conductors as coupled transmission-line sections, and their even-mode impedances account for the stray capacitance. Ideally, the capacitance is zero, causing the even-mode impedance to be infinite. The odd-mode impedance Z_{0o} is half the transmission-line impedance, and the even-mode impedance Z_{0e} should be as high as possible. Analysis shows that, for this type of balun, the even-mode impedance should be at least ten times the odd-mode. This is often accomplished in microwave mixers through the use of a suspended substrate; the air gap under and above the transmission line reduces its even-mode capacitance.

In planar mixers a high even-mode impedance is very difficult to achieve. Since the even-mode characteristic impedance $Z_{0e} = (L/C)^{0.5}$, where L and C are the even-mode inductance and capacitance, respectively, Z_{0e} can be increased either by reducing the capacitance or increasing the inductance. The latter involves winding the transmission line in a flat spiral, loading it with magnetic material, or winding it on a magnetic core.

A more complex balun, which has several desirable properties, is a version of the well known Marchand balun, shown in Figure 3. At first this appears to be a simple quarter-wave balun and an open-circuit stub; this stub electrically connects the right terminal of the load to the output of the left quarter-wave section.

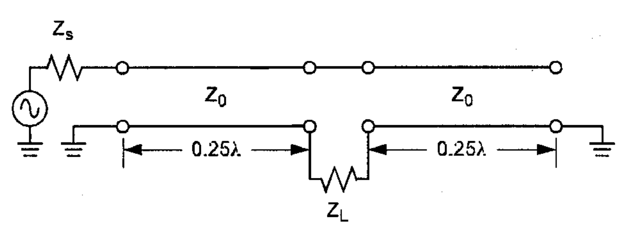

Fig. 3. A Marchand balun

What has been gained in this circuit, in comparison to the quarter-wave transmission-line balun? Two things: first, the Marchand balun tolerates low even-mode impedance. Although it is difficult to describe intuitively why this is so, analysis shows that the even-mode impedance need to be only about three times the odd-mode. Second, the symmetrical structure, having both output nodes connected to ground at dc, provides dc and IF returns for the mixer.

IF Baluns

None of the baluns described in the previous section have a structure analogous to the transformer's center tap. Without this, how does one connect the IF? Clearly, some other type of structure is needed. The obvious—and worst—solution is to use filters to separate the IF RF, and LO. This approach, although often used, does not allow the IF band to overlap the LO, one of the main advantages of the transformer-balun ring mixer.

A better solution is shown in Figure 4. This mixer uses quarter-wave RF and LO baluns and a four-wire IF balun [2]. Because this balun is excited in different modes by the RF/LO and IF, it separates these signals effectively. Specifically, lines 2 and 4 are excited by the LO, and realize a quarter-wave shorted stub, whose input impedance is ideally infinite; lines 1 and 3 affect the RF similarly. However, one pole of the IF excites lines 2 and 4, while the other excites lines 1 and 3. Thus, the four-wire line realizes a transmission line for the IF.

For optimum performance, the capacitance matrix of the coupled lines requires a symmetry that is difficult to achieve in practice: the main diagonal elements ideally are identical, as are the off-diagonal elements. In planar mixers, the symmetry closest to this ideal is achieved when one of the outer lines (usually line 4) is split into two pieces and located on either side of the structure.

Paradoxically, this circuit works *only* when the IF band overlaps the RF and LO.

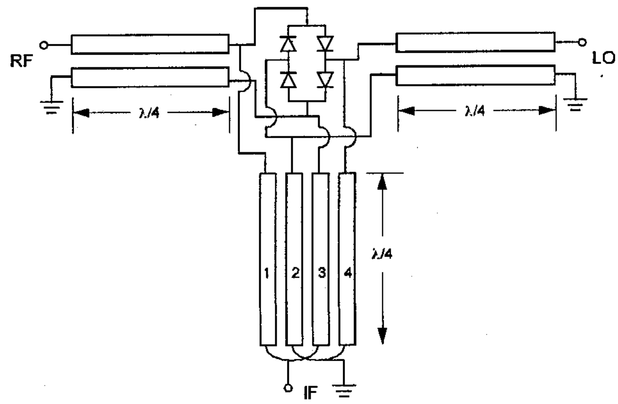

Fig. 4. A realization of the doubly balanced ring mixer using transmission-line baluns and a four-wire IF balun. Balun lengths are λ/4 at center of the RF/LO band. The four-wire balun allows the IF to overlap the RF or LO bands.

If low-frequency IF response is needed, blocking capacitors can be used at the outputs of the RF and LO baluns. These often create in-band resonances, however, so they must be used with care.

Examples of Planar Diode Circuits

Because of its tolerance for low even-mode impedances, the Marchand balun is ideal for use in planar circuits. Figure 5 shows a planar star mixer that has been realized as a GaAs integrated circuit [3].

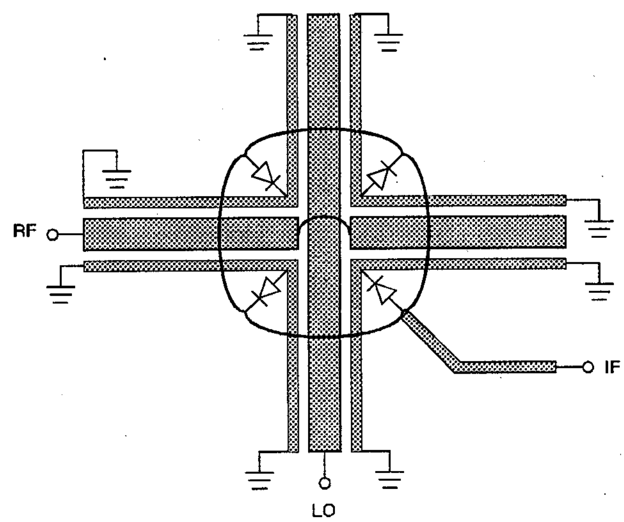

Fig. 5. A planar star mixer

The mixer uses two Marchand baluns oriented at right angles, one for the RF and another for the LO. The grounded conductors of each balun have been split into two strips, creating two outputs, and these are connected to the diodes. The IF connection is made to the common node of the diodes.

Unlike the ring mixer, the star mixer requires no IF balun, but the IF range cannot overlap the RF or LO. Within this restriction, the IF can be very broadband: we have produced versions of this mixer having 22-42 GHz RF and LO bands, and a dc-18 GHz IF. The conversion loss is approximately 7 dB and the third-order output intercept point is greater than 10 dBm.

A similar balun can be used for a frequency multiplier [4]. Figure 6 shows the multiplier. It is a realization of a full-wave bridge rectifier multiplier, which provides inherent rejection of the fundamental frequency and odd harmonics. The output balun is approximately half the length of the input balun. The latest versions of this multiplier display 10 dB conversion loss at an output frequency of 18 to 40 GHz. The conversion loss is very flat, varying only about 1 dB over this entire frequency range.

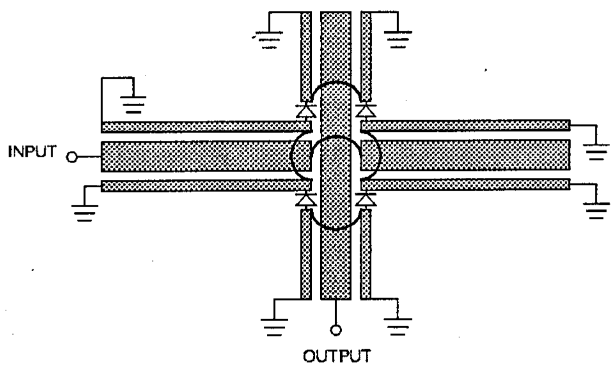

Fig. 6. A planar frequency multiplier. This is a microwave realization of a full-wave rectifier

A final example is a monolithic diode-ring mixer similar to that shown in Figure 4. This mixer exhibits approximately 9-10 dB conversion loss over RF and LO bands of 4 to 15 GHz, and an IF bandwidth of 1 to 12 GHz. It uses a four-wire IF balun and quarter-wave RF and LO baluns. The RF and LO baluns are arranged in a spiral; to avoid resonances, the spirals were modeled after a planar spiral inductor of known characteristics.

Conclusions

Practical, high-performance, low-cost planar mixers can be realized through careful attention to the design of their baluns. Marchand baluns and the use of creative measures to maintain high even-mode impedance in other types of coupled-line baluns are the key to realizing successful circuits.

References

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[4] S. A. Maas and Y. Ryu, "A Broadband, Planar, Monolithic Resistive Frequency Doubler," IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium Digest, pp. 443-6, 1994.