Schottky Octave Band LO Doubler

This paper describes a resistive Schottky-diode frequency doubler having an untuned output frequency range of 16 to 40 GHz. The multiplier uses a unique planar structure to achieve 12 dB average conversion loss at 13 dBm input power, 6 dBm maximum output power, and 20 dBC fundamental-frequency rejection.

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There is a great need for balanced frequency multipliers that exhibit broad, flat passbands, have good inherent harmonic rejection, and are compatible with monolithic processes. Even if it has low efficiency, a flat, broadband multiplier is an extremely useful component, one that can be used in mixer local oscillators, frequency synthesizers, FMCW radar (common to automotive radar) and a variety of other transmitter and receiver applications.

One of the most troublesome problems in designing balanced monolithic components is the lack of broadband planar baluns. Most baluns used in hybrid circuits are not planar, and thus are not useful in monolithic circuits. The few available planar baluns rarely cover a full waveguide bandwidth.

Achieving broad bandwidth in a frequency multiplier is also difficult. Varactor multipliers are inherently narrowband, and because of their high input Qs, FET multipliers are usually either narrowband and efficient or broadband and inefficient. Broadband FET frequency multipliers usually exhibit high conversion loss (about 10 dB, depending on the frequency range) and considerable passband ripple[1]. They also generate substantial

AM noise and, because they tend to amplify the input signal, often have poor fundamental-frequency rejection.

Schottky diodes do not have such severe inherent bandwidth limitations; however, there are two difficulties in the realization of such circuits as monolithic ICs[2],[3]. First, most conventional balun circuits are not planar, and second, multipliers using Schottky diodes are usually limited in bandwidth by the multiplier's baluns. Finally, third, resistive doublers are subject to a high theoretical minimum conversion loss. The maximum efficiency achievable with a resistive multiplier is n^{-2}, where n is the harmonic number[4]. Thus, a resistive doubler can achieve no better than 6 dB conversion loss. In practice, obtaining good conversion efficiency is difficult, and conversion loss below 10 dB is rarely achieved, even in narrowband circuits.

We have addressed and solved these problems by realizing the multiplier as a balanced structure, *using resistive Schottky-barrier diodes for the* multiplier's nonlinear elements, and by using a new type of broadband planar balun. It is essentially a multistrip Marchand balun, realized in a coplanar configuration. The balun is similar but not identical to one used successfully for the realization of monolithic star mixers[5]. This structure is very broadband, covering in excess of two waveguide bandwidths simultaneously, provides excellent fundamental-frequency rejection, and can be modeled accurately for CAD purposes.

The efficiency of our multiplier is modest in comparison to narrowband FET and varactor circuits. However, the approximately 6 dBm maximum output power is adequate for many applications, and broadband monolithic FET and HEMT amplifiers can be used to amplify the output in those applications wherein more power is needed.

Basic Structure

The multiplier is a microwave realization of the full-wave bridge rectifier shown in Figure 1. This circuit has the useful characteristic that its output current contains only even harmonics of the input frequency. As such, output components at the fundamental frequency and at other odd harmonics are inherently rejected. Additionally, because the high even harmonics in resistive diode multipliers are invariably weak, all unwanted even harmonics are usually rejected effectively as well.

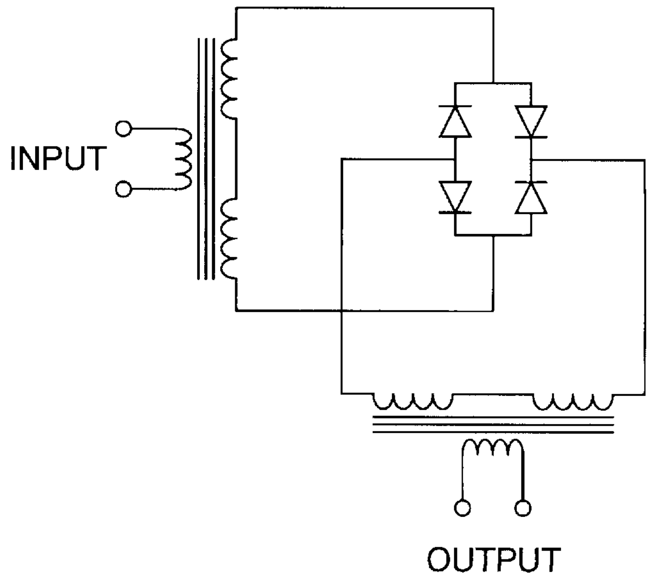


Figure 1. Diode multiplier in its ideal, transformer configuration.

At VHF and UHF, where practical transformers are possible, a multiplier can be realized literally as shown in Figure 1. However, for microwave circuits, baluns must be used instead of transformers. The resulting microwave circuit is shown in Figure 2, in which two coupled line baluns replace the transformers.

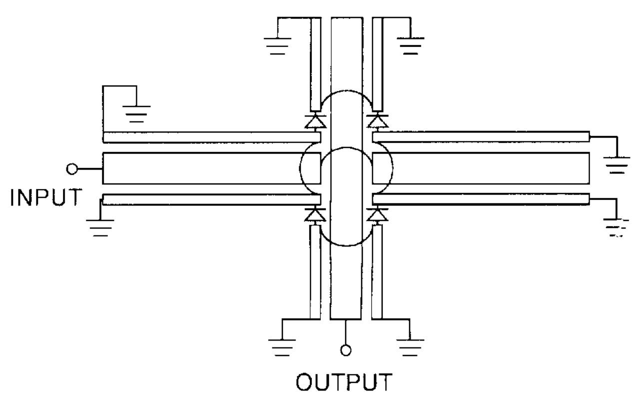
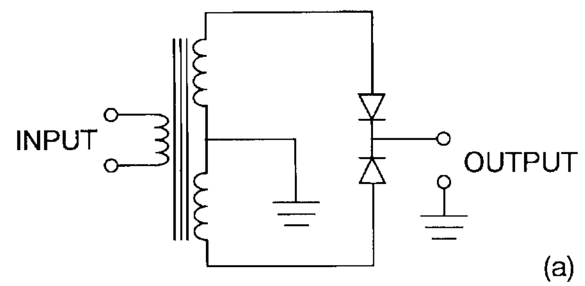


Figure 2. Diode frequency doubler in monolithic form.

Ther full-wave rectifier multipliers, realized with either two or four diodes, are possible. Two circuits are shown in Figure 4. Figure 3 (a) shows a two-diode circuit. This circuit requires a current return through the center tap of the transformer. This would not be a problem if an ideal transformer could be used, but the residual inductance of a real transformer is in series with the output, and increases the loss. In microwave realizations, a balun is used instead of a transformer, and baluns, of course, do not have a center tap.



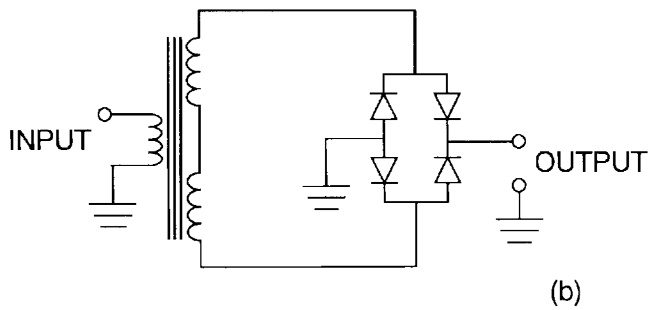


Figure 3. Two other possible bridge-rectifier multipliers: (a) a two-diode circuit and (b) a four-diode circuit using only one balun. A transformer cannot be used in circuit (b).

An alternate four-diode circuit is shown in Figure 3b. This circuit does not require an output balun, and as such appears to be superior to the circuit of Figure 1. However, it has a tragic flaw: unless the even-mode output impedance of the balun is very high, the two diodes connected between the balun and ground are loaded by the balun. This unbalances the structure and degrades fundamental-frequency rejection.

The four-diode multiplier is especially well suited to microwave realization because no current return is needed in either of the baluns, and the impedances of the balun, source, and load resistances are usually easy to realize. The connection points of the input balun are virtual grounds for the output, and vice-versa. Thus, good balance is ssured.

An advantage of the bridge rectifier is that it can be used when the input and output frequency ranges overlap. Fundamental-frequency rejection depends on the quality of the baluns; in particular, a high even-mode impedance in the coupled-line sections is necessary.

In the design of circuits using baluns we attempt to use, as much as possible, only circuits that can be characterized accurately. Complex elements, such as spiral transformers and lumped-element hybrids, are likely to have spurious resonances and are likely to be difficult to model well. Our baluns use only straight coupled transmission lines. These have predictable characteristics and can be modeled accurately using computer simulation.

The design of a frequency multiplier requires the determination of the source and load impedances seen by the diodes. For a balanced multiplier, these can be found by reducing the circuit to a single-diode equivalent, and using methods described in #[6]. In this type of multiplier the source and load impedances of the single-diode equivalent circuit are fortuitously the same as those of the balanced multiplier, and are in the neighborhood of 40 ohms.. To resonate the small junction capacitances of the diodes, the source and load impedances must have a small inductive component as well.

Baluns

The input and output baluns are realizations of the classical Marchand balun[8]. They consist of a simple coupled-line structure. We have used similar baluns extensively in broadband diode mixers #[5].

Design of such baluns is very simple, mainly because there are only two parameters available to the designer: the length and the odd-mode impedances of the coupled lines. (The even-mode impedance is made as high as possible, and is ideally infinite.) Viewed as a transmission line section, the balun is used as a quarter-wave transformer between the 50 ohm source and the diode load, determined by harmonic-balance analysis to be approximately 40 ohms. The odd-mode impedance of the balun equals half its transmission-line impedance. Thus, we have

$$(1)\quad Z_{oo} = 0.5\sqrt{Z_s Z_d}$$

where Z_s is the source impedance and Z_d is the calculated diode impedance. This gives an odd-mode impedance of approximately 22 ohms. The length of each half of the structure is 0.25 wavelengths. This is reduced slightly to compensate for the junction capacitance of the diodes. The degree of length reduction is determined empirically during harmonic balance simulation.

Most harmonic-balance simulators do not include a nonhomogeneous three-line coupler. Each side of the balun is modeled, for CAD purposes, as two-strip couplers in parallel. Although this model is not exact, it is surprisingly accurate. It was tested by means of appropriate software #[7]. Alternatively, one could simply calculate the even and odd-mode impedances by any appropriate method and model the coupled lines in the simulator by their even- and odd-mode parameters.

Realization

A schematic diagram of the multiplier is shown in Figure 2, and a photograph of the multiplier is shown in Figure 4. The baluns consist of three strips: the center strip is excited, and the two strips on either side, the coupled strips, are connected in parallel. The use of two coupled strips is necessary for achieving the desired odd-mode impedance. Even-mode impedance is maximized by using narrow transmission lines in the baluns, consistent with achieving low loss, and a 635 mm thick substrate. We were not have been able to achieve an adequate even-mode impedance had the more conventional 100-mm thick substrate been used.

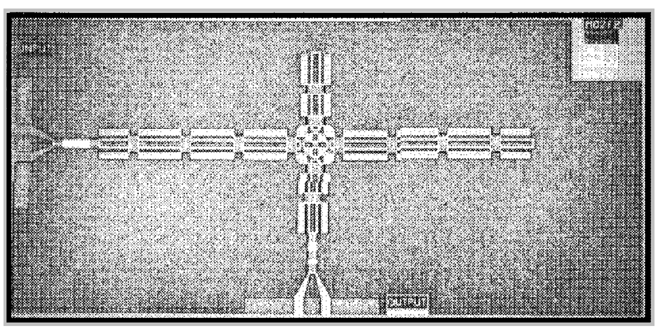


Figure 4. Photo of the frequency multiplier. The multiplier has coplanar-waveguide interfaces. The upper surface is a ground plane. Air bridges are used to prevent the generation of slotline modes in the balun structure.

The multiplier is realized in HBT technology. The diodes are Schottky structures consisting of a metal anode deposited on the collector layer of a heterojunction bipolar transistor (HBT) structure. The anode is recessed slightly to reduce the diode's series resistance. Because of the very light doping in this layer, a relatively large 10 mm x 10 mm square anode is necessary to achieve low series resistance. The resulting parameters are c_{j0} = 0.026 pF, R_s = 8.1 ohm, and h = 1.043.

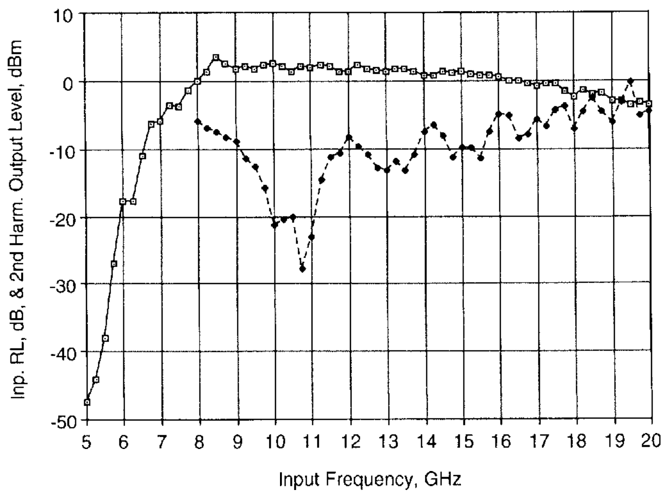


Figure 5. Second-harmonic output power (solid line) and input return loss (dashed line) of the diode doubler. P_{in}=13 dBm.

Performance

The multiplier's conversion loss, at P_{in}=+13 dBm, is shown in Figure 5. Optimum conversion loss is achieved at this level, but higher output power is possible with greater drive. The roll-off above 18 GHz is caused by the degradation of the input return loss, which improves with increased input power. At an input of +16 dBm the bandcenter conversion loss increases only 1 dB. Fundamental-frequency isolation, shown in Figure 6, is greater than 20 dBC at 13 dBm input level between 13 and 20 GHz. This implies that the input-to-output isolation is above 30 dB across

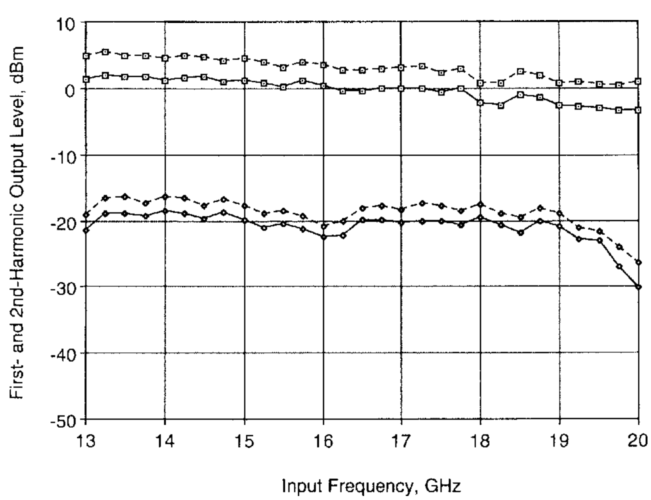


Figure 6. Fundamental-frequency and second-harmonic output power from 13 to 20 GHz at P_{in}= +16 dBm (dashed lines).

the band. This remarkably high rejection results from the excellent balance of the baluns.

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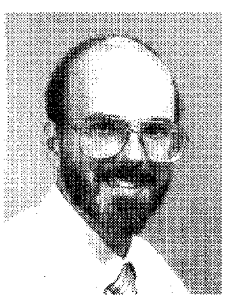

Steve Maas received BSEE and MSEE degrees from the University of Pennsylvania in 1971 and 1972, respectively, and the Ph. D. in Electrical Engineering from UCLA in 1984. He joined the National Radio Astronomy Observatory in 1974, where he designed the low-noise receivers for the Very Large Array radiotelescope. Subsequently, at Hughes Aircraft Co. and TRW, he developed low-noise microwave and millimeter-wave systems and components, primarily FET amplifiers and diode and FET mixers, for space communication. He also was employed as a Research Scientist at The Aerospace Corp., where he was engaged in the optimization of nonlinear microwave circuits and the development of circuit-design software based on harmonic-balance, Volterra-series, and time-domain methods.

Steve joined the UCLA Electrical Engineering Faculty in 1990, left it in 1992. Now, as President and Principal Consultant of Nonlinear Technologies, he consults independently and develops nonlinear circuit analysis software.

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Young Ryu received BSEE (1982) and MSEE (1986) degrees in Electrical Engineering from the University of California, Los Angeles. He joined TRW RF Product Center's technical staff in 1987 where he has been engaged in the development of high performance microwave and millimeterwave circuits for space communication. He has developed several MIC and MMIC components including amplifiers, mixers, multipliers using HEMT, HBT and MESFET devices.

Young Ryu is author and co-author of two technical papers. He enjoys amateur radio and RC flying.