Computer-Aided Design of Microwave Frequency Doublers Using a New Circuit Structure

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***Abstract*—A new circuit structure for microwave frequency doublers is presented, which features effective suppression of fundamental and odd harmonics (> 50 dB), conversion gain (> 3 dB), and simplicity of the circuit itself. Furthermore, it can be used in both balanced and unbalanced output configurations, without requiring baluns or transformers. A novel differential amplifier developed as part of the doubler circuit is also described in detail. It used an inductor to replace the active current source in conventional differential amplifiers, which simplified the circuit and, more importantly, enabled the amplifier to operate at high microwave frequencies. Experimental results are given in the paper.**

I. Introduction

FREQUENCY doublers are widely used in microwave subsystems as part of multiplier chains or for other purposes. Typically, frequency doubling is realized by feeding the signal through nonlinear devices, such as diodes or transistors, and then extracting the second harmonic and rejecting other frequency components. The basic problem in designing a doubler is that of achieving sufficient suppression of undesired signals at the output port, while obtaining good conversion performance. Circuit components such as microstrip quarter-wavelength or radial open stubs can be used in the output port of the doublers [1], [2], which shunt the fundamental frequency component to ground to prevent it from appearing at the output. Similar techniques may also be used at the input port to short-circuit the second harmonic to ground to achieve good input–output port isolation. However, these techniques are limited to narrow band applications, because microstrip quarter-wavelength open stubs are difficult to realize over a wide range of frequency. Rejection of the unwanted harmonics over a wider bandwidth can be achieved using balanced configurations, such as those described in [3] and [4], since the fundamental and odd harmonics are inherently suppressed in the circuits. A drawback associated with these structures is the requirement for baluns or transformers, which increase the loss, physical dimensions, and complexity of the circuits.

A new circuit structure has been developed for microwave frequency doublers. It features effective suppression of fundamental and odd harmonics, conversion gain, and simplicity of the circuit. Furthermore, either a balanced or unbalanced configuration can be selected at the output without requiring baluns or transformers, thereby reducing the loss and simplifying the circuit. Nonlinear computer simulation was carried out during the design of an MMIC double using the present circuit configuration. Very good performance of the circuit was predicted and then verified by experimental results. In the following, the proposed circuit structure is illustrated, together with a description of the principle of its operation, circuit implementation, design considerations, and measured results.

Manuscript received March 26, 1993; revised June 22, 1993.
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IEEE Log Number 9213018.

II. The Doubler Circuit and Its Operation

The doubler circuit is shown in Fig. 1. It consists of a diode bridge functioning as a full-wave rectifier, a differential amplifier using a pair of transistors, and three simple dc-decoupling and matching circuits, used at the input, the output, and between the rectifier and the amplifier.

The input signal at frequency f is applied to node 1 of the circuit and is full-wave rectified by the diode bridge. The two outputs from the rectifier at nodes A and B are applied to the differential amplifier, which in turn also supplies two outputs. These can be then used in either balanced or unbalanced configuration.

Both odd- and even-order harmonics are generated by the full-wave rectification. The odd and even harmonics have different relative phase relationships at the output nodes of the rectifier (A and B). The fundamental component and all odd harmonics at nodes A and B are in a common mode (in phase), with equal amplitudes when the circuit is symmetric, which in practice can well be realized using MIC and MMIC technologies. These harmonic components are effectively suppressed by the amplifier because of the common mode rejection characteristics of differential amplifiers. Further suppression is achieved if the two outputs of the amplifier are used in a balanced configuration. In addition, in both unbalanced and balanced configurations, good suppression performance of the circuit is obtained. This is one of the desirable features of the present frequency doubler circuit structure.

In contrast to the odd harmonics, the even harmonics at the output of the rectifier are in a differential mode (out of phase). The desired second harmonic is generated at a relatively strong level by the full-wave rectification and is

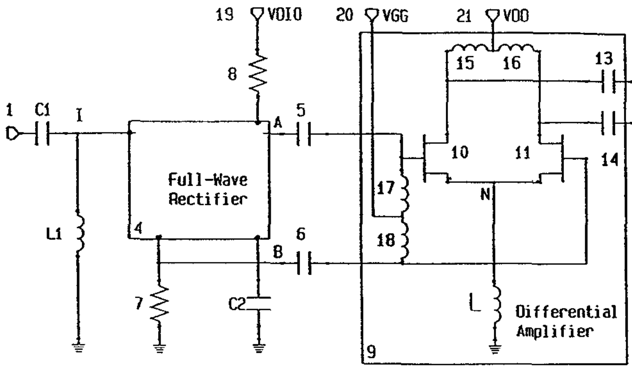

Fig. 1. Proposed frequency doubler circuit.

then further amplified by the differential amplifier. Although other even harmonics (fourth, sixth, · · · ,) are in a differential mode, their levels are lower than that of the second harmonic. In addition, and more importantly, they are sufficiently removed from the second harmonic so that they can be filtered out relatively easily by the frequency response of the circuit. A balanced output signal can be obtained between the two output nodes (2 and 3) of the doubler. Otherwise, if unbalanced output signals are desired, they can be obtained directly at the two output nodes.

It can be seen from the above discussion that there are a number of advantages in using the full-wave rectifier–differential amplifier combination for frequency doubling. For a given CW signal, full-wave rectification generates relatively high level of second-harmonic content. Diode rectifiers require a very limited amount of DC power (if any), depending on whether or not biases are employed. As for the differential amplifier, its properties of rejecting common mode input signals and amplifying differential mode signals are both desirable and fully utilized in the present application. It is especially advantageous that the suppression of the unwanted fundamental and odd harmonics is realized by mode rejection, instead of frequency filtering, which allows the doubler circuit to operate over a wider bandwidth with satisfactory performance.

III. Circuit Implementation and Simulation

In order to realize the advantages of the doubler circuit described above, unique circuit configurations have been developed to implement the full-wave rectifier and, in particular, the differential amplifier shown in Fig. 1, which are described in detail in the following. Also discussed in this section are device modeling and circuit simulations.

A. The Full-Wave Rectifier

A detailed schematic for the full-wave rectifier is shown in Fig. 1, where 4 is a quad diode bridge, C_1 and L_1 are input matching components, and C_2 connecting the diode bridge and ground is a dc decoupling capacitor. Optional bias applied to the diodes is provided via the resistors shown in the schematic. Since the biasing current for the diodes is small, they are large enough such that the RF power dissipation across them are negligible. In addition to its major functions of rectifying RF input signal and generating the wanted second harmonics, the diode bridge in the doubler circuit plays the role of implementing the unbalanced to balanced transformation. This eliminates the need for baluns or transformers, which are otherwise usually employed to realize the transformation. The input stage of the present circuit is hence simplified and disadvantages associated with baluns such as limited bandwidth, insertion loss, and large physical dimensions are removed.

B. The Differential Amplifier

Differential amplifiers have desirable properties that are well suited to the present frequency doubler application, as mentioned in Section II. However, it is rare to find them working at microwave frequencies above a few gigahertz. Transistor-based current sources with decent performance are difficult to realize at these microwave frequencies because of the parasitic effects of the devices and other components. This prevents the realization and applications of differential amplifiers at such frequencies. A novel structure for differential amplifiers (Fig. 1) has been developed to solve this problem, extending the operating frequency limit of the circuits significantly. Note that in Fig. 1, an inductor L is used in place of an active current source, which is connected between node N and ground. Its inductance is chosen to be sufficiently large to make the RF current component flowing through it negligible and to keep the total current of the two transistors constant. As a result, at microwave frequencies, this inductor acts as a simplified and yet greatly improved current source replacing the active ones used in conventional differential amplifiers. Furthermore, the higher the frequency, the better the inductor functions due to its higher impedance, until of course, the parasitics take over. Today, lumped inductors operating satisfactorily up to 25 GHz are realizable using MMIC and HMIC (miniature hybrid microwave integrated circuit) technologies.

C. Circuit Simulation

Nonlinear simulation of the circuit shown in Fig. 1 was carried out using a microwave computer-aided design software package. Parasitics associated with the components were taken into account, in order to accurately predict the performance of the circuit. Optimization and yield analysis were also carried out to optimize the operation of the circuit in terms of conversion gain, return loss, suppression of fundamental and unwanted frequency harmonics at the output, etc., over the range of frequencies and power levels of given input signals.

The large-signal model for the diodes is given in Fig. 2, where $I(V)$ represents the I–V characteristics of the diodes, $C(V)$ is the Schottky junction capacitance, and R_s is the parasitic series resistance of the diode. The rectifi-

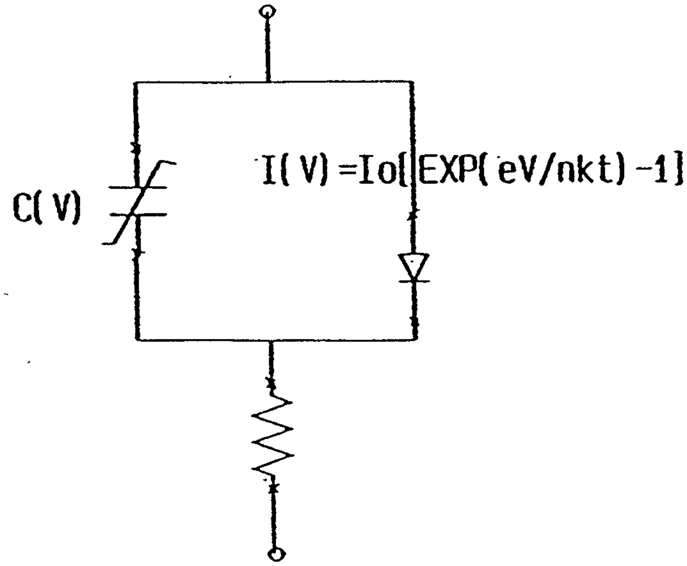

Fig. 2. Nonlinear circuit model for diodes.

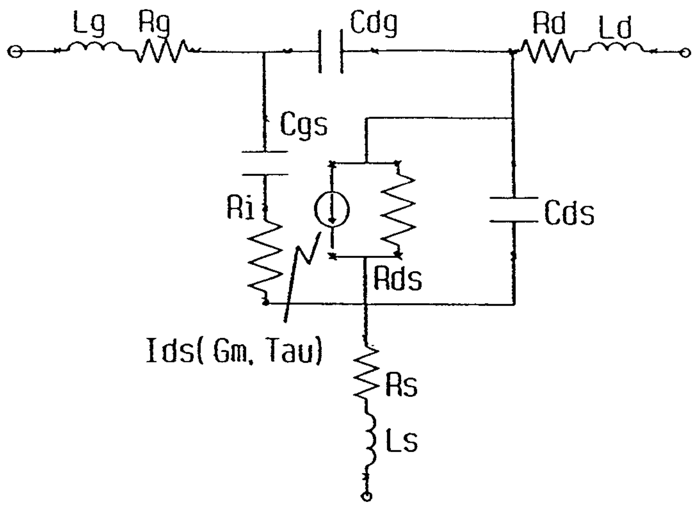

Fig. 3. Small-signal model for MESFET's.

cation and frequency doubling of the input signals are realized due to the nonlinear I–V relationship, which can be expressed as [5]

$$I(V) = I_0 \exp\left(\frac{eV}{nkT} - 1\right)$$

where

- I is the diode current
- I_0 is the saturation diode current
- V is the voltage applied to the diode
- K is Boltzmann's constant
- I is the absolute temperature
- e is the electron charge
- n is the ideality factor.

n is a number close to unity, usually varying between 1.05 and 1.4 for different diodes. It was selected so that the I–V curve obtained matches the measured data for the diodes.

The nonlinear capacitance of the diodes also considerably affects the performance of the rectifier, which is a function of the voltage applied to the diodes:

$$C(V) = \frac{C_{j0}}{\left(1 - \frac{V}{V_{bi}}\right)^{1/2}}$$

where

- $C(V)$ is the Schottky junction capacitance of the diodes
- C_{j0} is the capacitance at zero bias
- V_{bi} is the built-in potential.

The parameters of the diode were optimized together with C_1 and L_1 in the input circuit of the doubler shown in Fig. 1, in order to match the input of the rectifier to the signal source impedance. This was performed under the specified input signal levels such that good return loss of the circuit was obtained in practical operations. Both computer simulation and experiments showed that circuit performance was dependent on input power, particularly at low levels. Details of the performance of the doubler circuit will be given in the following section, where the experimental aspects of an MMIC doubler based on the proposed configuration is described.

Efforts have also been made to accurately model other components used in the circuit, including various passive elements and the MESFET's in the differential amplifier. Since the MESFET's operate in the linear region, it is sufficient to use small-signal equivalent-circuit models to describe their behavior in the computer simulation. The circuit model for the FET's is shown in Fig. 3. The values of its component parameters were obtained by fitting the computed S-parameters for the equivalent circuit to the measured data.

DC bias applied to the diode bridge is optional to achieve optimum performance of the rectifier for different input power levels. For lower levels of input signals, it is useful to bias the diodes to operate at a point close to the knee of their I–V curves. However, for higher input power levels, biasing will not significantly contribute to conversion efficiency. The transistors in the differential amplifier should be biased for operation in their linear amplification regions. Under this operating condition, the circuit amplifies the wanted second harmonics of the input signal and generates no additional higher order harmonics at its output. The linear operation is also required for maintaining the electrical symmetry of the circuit. Otherwise, the performance, in particular the common mode rejection ratio (CMRR), of the differential amplifier will deteriorate.

III. Experimental Results

Using the above described circuit structure, an MMIC frequency doubler has been designed, fabricated, and tested. The doubler was intended to be used as part of an EHF satellite communication receiver, with an input

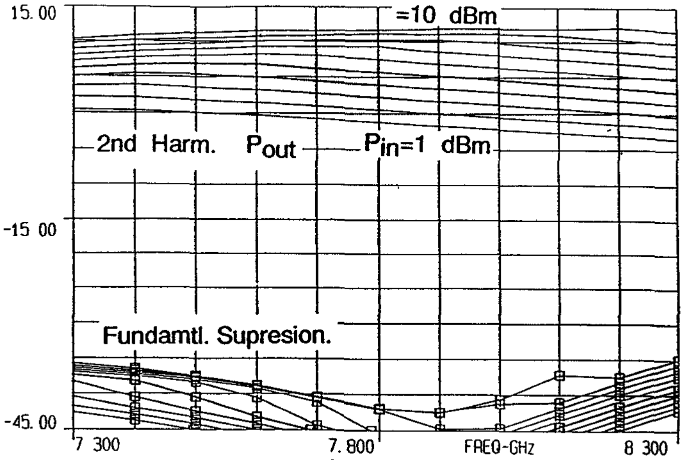

Fig. 4. Simulated output power and fundamental frequency suppression.

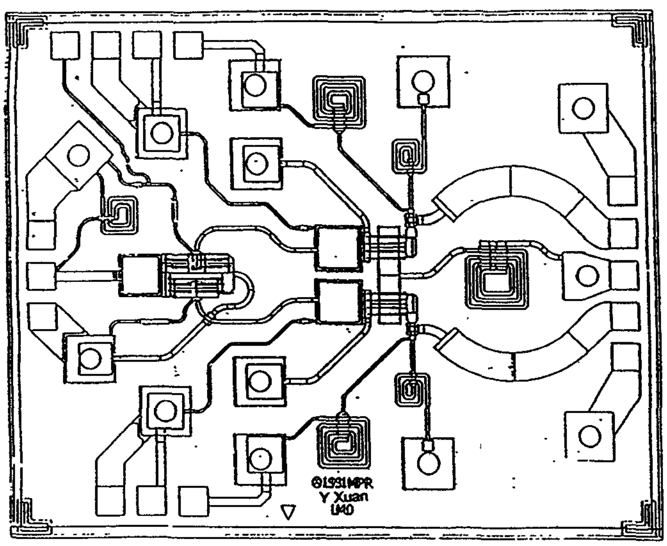

Fig. 5. MMIC doubler circuit layout.

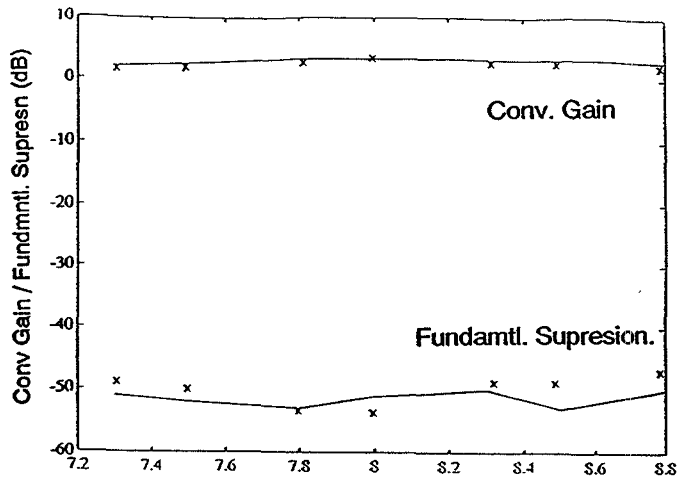

Fig. 6. Measured (curve) and simulated (cross) conversion gain, and fundamental suppression versus input frequency (GHz).

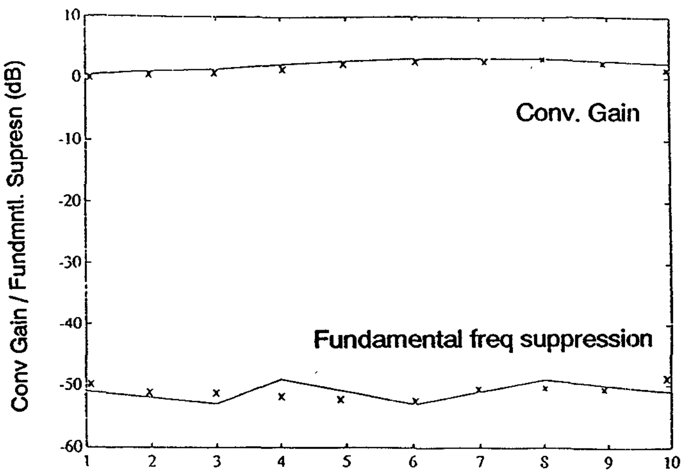

Fig. 7. Measured (curve) and simulated (cross) conversion gain, and fundamental suppression versus input power (dBm).

power level of 6 dBm at about 7.8 GHz. Fig. 4 shows the simulated second-harmonic output power and the suppression of the fundamental frequency component as functions of input signal frequency and power level. The layout of the circuit is shown in Fig. 5, where the two key blocks—the full-wave rectifier and the differential amplifier—are indicated. The size of the fabricated chip was about 1.7 × 2.9 mm, which was dictated by the project on the multicircuit wafer, rather than the doubler circuit itself. The actual area required by the circuit was substantially smaller and was about 1.8 × 1.9 mm. Further size reduction of the circuit to an area of about 2.5 mm^2 is possible, if so required, but attention must be paid to account for the parasitic effects, such as the mutual coupling among the components in the circuit. Bias circuits for both the rectifier and the amplifier are included within the chip. Special attention has been paid to keep the symmetry of the physical layout, although computer simulation showed that the circuit would work satisfactory with up to 10 percent of dimensional tolerance in fabrication. The circuit has been successfully tested with consistent results. The measured fundamental suppression was found to be over 50 dB, while better than 3 dB conversion gain was achieved. This can be seen in Fig. 6, where the frequency response of gain and fundamental suppression is shown, together with the relevant predicted results. Outside the frequency range given in the figure, the circuit is still useful, but its performance will gradually degrade. However, it is emphasized that the operating bandwidth of this particular doubler—which was designed for single frequency operation—does not represent the bandwidth limits that are achievable using the new circuit structure presented in this paper. Reasons supporting this claim have been discussed in the previous sections. The measured and simulated dependence of the conversion gain and fundamental suppression on the input power level is given in Fig. 7. It can be seen from Figs. 6 and 7 that the measured conversion gain agrees very closely with the simulated results. As for the fundamental frequency suppression, there is a discrepancy of a couple of decibels at some of the frequencies. However, this represents only a very minor difference between the measured and simulated power levels, because the absolute power considered is already very low (around −45 dBm). This reasonable discrepancy may be caused by fabrication tolerances and some inaccuracy in modeling the circuit nonlinearities and parasitics.

IV. Conclusion

A new circuit structure for microwave frequency doublers has been presented. It has been used in the design of an MMIC doubler. Its major advantages are effective suppression of the unwanted fundamental and odd-order harmonics and conversion gain to the desired second harmonic. They have been demonstrated by computer simulation and further verified by measured results for the MMIC circuit. Furthermore, the circuit requires no baluns or transformers and both a balanced or unbalanced output is available. The differential amplifier successfully developed and used in the doubler circuit is unique in that it employed an inductor to replace the active current source in conventional differential amplifiers. This extends the operating frequency of microwave differential amplifiers and simplifies the circuit structure.

Acknowledgment

The authors wish to acknowledge the cooperation of their colleagues and thank Dr. W. Bosch for his advice during the development of the circuit.

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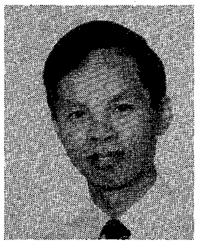

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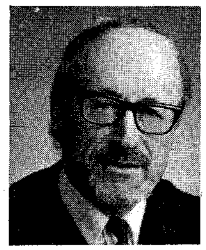

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