WIDEBAND MESFET MICROWAVE FREQUENCY MULTIPLIER

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ABSTRACT

New wideband, high efficiency GaAs MESFET microwave multipliers have been investigated at 8 and 12 GHz. These units, for frequency synthesizing and phase-locked source applications, require low driving power and have low distortion.

Introduction

With the advent of GaAs MESFET's in recent years, microwave low noise amplifiers, modulators, limiters and oscillators have been fabricated and demonstrated with remarkably high performance. A MESFET frequency multiplier, however, has not been reported. Modern microwave frequency synthesizers and phase-locked sources demand wideband and low noise frequency multipliers with high efficiency and low driving power. This paper describes a single GaAs MESFET frequency doubler which performs parametric harmonic generation and amplification simultaneously at 8 and 12 GHz output frequencies.

In the past, bipolar transistors have been employed in the design of frequency multipliers below C-band in Class-C amplifier configuration. The frequency response and power handling capability of bipolar transistors are limited, and because of its poor reciprocal isolation (large S_{12}), well designed idlers are required to suppress undesired leakages. Varactors and step recovery diodes have been utilized for harmonic generation in a broad frequency range. However, these devices have low multiplying efficiency, with multiplication loss instead of gain, and require high RF driving power (500 mW on the average). Further, the bipolar transistor has exponential transfer characteristics which require multiple traps to suppress higher harmonics and maintain output waveform. In contrast, the MESFET frequency doubler provides high conversion efficiency and requires low driving power. The performance comparison of these four different multipliers is shown in Table I.

Operation Principle

The study of frequency multiplication is based upon the simplified equivalent circuit of the MESFET, depicted in Figure 1. The frequency dependent nonlinearities of the device include the gate-to-source capacitance (C_{gs}) nonlinearity, the nonlinear transfer characteristics, the gate-to-drain capacitance (C_{gd}) nonlinearity and the output conductance (G_{ds}) nonlinearity, all of them can be represented by the Volterra-Series. The C_{gs} nonlinearity is caused by the Schottky-barrier between gate and source, and it shows characteristics analogous to Schottky-barrier diodes that are most useful for microwave varactor frequency multipliers. The rest of the nonlinearities are I_d-V_{gs} nonlinearities caused by the pinch-off effect. The frequency multiplier can thus perform in one of the following three modes, according to the selection of the active device and its operating bias conditions;

Table I. Comparison of Microwave Frequency Multipliers

	Diodes	Bipolar Transistor	MESFET
Bandwidth	Narrow	Medium	Wide
RF Driving Power	300 mW	100 mW	10 mW
Output Frequency	SRD: 18 GHz Varactor: 120 GHz	11 GHz	30 GHz
RF Efficiency	50-70%	60%	90-200%
Isolation	Poor	Medium	Excellent
Idlers	Critical	Critical	Less Critical
Power Handling at X-Band	1-4 W	0.5 W	1-4 W
Multiplier Stability	Good	Poor	Excellent
Higher Harmonics Distortion	High	Low	Very Low

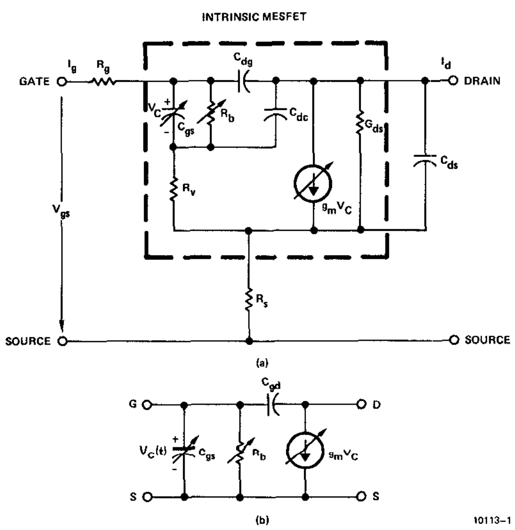

Figure 1. (a) MESFET Equivalent Circuit and (b) Simplified Intrinsic MESFET Equivalent Circuit

- Nonlinear Schottky-barrier gate capacitance - amplification mode
- Time-varying nonlinear transconductance - amplification mode
- A combination of the two modes

The third configuration is described in this paper.

For simplicity, the minor nonlinearity contributed by the barrier resistance, R_b, is neglected in the analysis. When the signal is applied between the gate and the source, the MESFET operates as two sections; the Schottky-barrier diode containing C_{gs} functions as a varactor producing harmonics, and the device transconductance simultaneously provides amplification at fundamental as well as harmonic frequencies. The voltage-dependent input capacitance is approximately given as[1]

$$C \approx \frac{C_{gso}}{\sqrt{1 - \frac{V_c}{\phi}}} + C_{gd}\,(1 + g_m R_L) \qquad (1)$$

where C_{gso} is the C_{gs} at zero bias, ϕ is the diffusion potential, and $g_m R_L$ is the voltage amplification factor. The voltage-dependent transconductance, g_m also generates a strong second and negligible high order harmonics due to its almost square-law transfer (I_d - V_{gs}) response. The gate-voltage-dependent transconductance can be expressed as:

$$g_m = 2\left(1 + \frac{V_c}{V_p}\right)\frac{I_s}{V_p} \qquad (2)$$

where V_p is the pinch off voltage and I_s is the saturation current at V_{cg} = 0 V.

Manley and Rowe[2] indicated that a lossless nonlinear capacitance as a harmonic generator can convert up to 100 percent of the available generator power into a single harmonic with proper tuning and impedance matching. Practically, the lossy elements in MESFET's reduce the conversion efficiency. The harmonics generation efficiency as Schottky-barrier gates of MESFET's depends upon the nonlinear C_{gs}, input resistance, idler forward conductive angle, load resistance, and the total effective Q of the circuit. The input resistance contains the parasitic contact resistances R_g and R_s, and source-gate changing resistance, R_i. This resistance contributes to the degradation of frequency multiplication efficiency. The total, effective Q includes the device Q and the circuit-loaded Q. High Q configuration results in low conversion loss and low noise. At the same time, it also reduces the operational bandwidth.

Through the simultaneous process of nonlinear capacitance frequency conversion at Schottky-barrier gates, and drain current amplification, the overall maximum conversion gain of the MESFET multiplier - under impedance-matched conditions - can be approximately expressed as:

$$G_{Tn} \simeq \frac{g_m}{4G_d} \cdot L_n \cdot \frac{\left|Z_n + R'_{in}\right|^2}{R_e\,(Z_n)}\,, \qquad n = 1, 2, 3, \ldots \qquad (3)$$

where n is the harmonic number and n = 1 is the signal (fundamental) frequency. R'_{in} is R_{in} at the operating bias condition. Z_n is the gate impedance at the designated harmonic frequency. L_n is the minimum conversion loss of n_{th} harmonic at the Schottky-barrier gate. Both Z_n and L_n can be derived and computed by the V_{gs} - I_g matrix operation at signal and harmonic frequencies. All variables such as signal driving power, nonlinearity capacitance and lossy elements (R_{in}) must be considered in the calculation. The large device input resistance, $R_{in} = R_g + R_i + R_s$, resulting in a large conversion loss, L. Therefore, MESFET's with small G_d and R_{in}, and large g_m can produce a high overall gain, G_{Tn}.

The stability conditions of lossy varactor multipliers have already been extensively discussed elsewhere.[3] Absolutely stable conditions seriously limit the overall varactor multiplication efficiency. In MESFET frequency multiplier designs, one has to optimize the Schottky-barrier gate stability-efficiency relationship to avoid spurious tones, and also to prevent oscillation in the amplification stage. The S- or lumped-parameter of the FET can be utilized to compute the well-known transistor stability factor, K.

The lack of an idler circuit makes MESFET multipliers reasonably broadbanded with low AM-to-PM conversion noise. The GaAs MESFET has low intrinsic and thermal noise, but it also has flicker noise spectrum, exhibiting an 1/f-like character near the carrier frequency. The flicker noise performance depends mainly upon the device itself, even though the high Q circuit may help to limit its spreading range.

The multiplier can also be fabricated in common-gate configuration, presenting the advantages of better input and output VSWR's in comparison with common-source operation. In general, however, this configuration has slightly higher noise, lower power gain and is less stable.

Experiments

Both common-gate and common-source packaged DXL-3501A MESFET's have been investigated as frequency doubler experiments. The latter configuration offers much higher conversion efficiency. As shown in Figure 2, the common-source configuration was fabricated on a 30 mils thick low cost Teflon-fiberglass (TFG) substrate with an appropriate bias circuit design. The doubler, with 8 GHz output frequency, has 1 dB gain, and at 10.0-12.5 GHz output has 1.1 ±0.3 dB loss, biased at V_{gs} = -3.2 V, V_{ds} = 3.0 V and I_d = 10 mA, with +12 dBm RF driving power. The 10.0-12.5 GHz doubler has the same performance at zero bias when the RF driving level increases up to +16 dBm. No parametric oscillation or relaxation

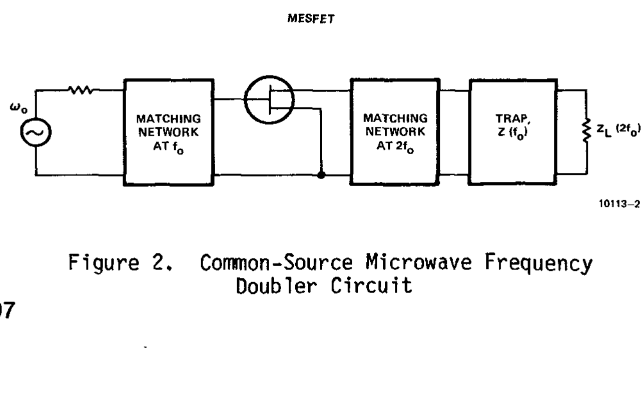

Figure 2. Common-Source Microwave Frequency Doubler Circuit

oscillation was observed at any bias conditions. The third- or higher-order harmonics amplitude is too small to measure while the fundamental signal rejection is better than 55 dB across the band.

The NEC 38806 packaged device was also investigated at 12 GHz on the TFG substrate. It has a 2 dB conversion gain and a -52 dB third harmonic distortion. Unfortunately, the device was damaged due to a signal generator transient before any meaningful data were taken.

Discussion and Conclusion

A single common-source MESFET has been utilized to fabricate wideband microwave frequency doublers. Compared to conventional approaches, the new multiplier provides design simplicity, higher conversion efficiency, better isolation, lower noise performance and an inherently wider bandwidth. Moreover, it requires very low RF driving power. The experimental results will be further improved if chip MESFET and fused-silicon alumina substrates are used instead of packaged devices and TFG substrates. Ka-band frequency multiplying is achievable by selecting high f_{max} devices. Besides the parametric reactance and time-varying transconductance multiplier discussed in this paper, the MESFET may also be used in a switching reactance multiplication mode, by which the SRD multiplier is operated.

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