A 45 GHz Highly Stable +15 dBm Low Noise GaAs MESFET Source Using a GaAs PHEMT as a Frequency Doubler

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Introduction

The rapid increase in applications for mm-wave technology has resulted in the need for efficient and highly stable oscillators. Until recently, a Gunn oscillator was the only choice for a low noise source with reasonable power output at frequencies above 30 GHz. The advancement of GaAs MESFET and PHEMT technology has made it possible not only to generate signals at mm-wave frequencies, but to process them through frequency multipliers and amplifiers at levels not attainable without the bulk devices until recently. This paper describes the design approach and practical realization of a 45 GHz source, as shown in Figure 1. Using a low noise GaAs MESFET DRO at 22.4 GHz, followed by a GaAs PHEMT frequency doubler and GaAs MESFET buffer amplifier, +15 dBm power has been achieved at 45 GHz. The phase noise of −82 dBc/Hz at 10 kHz and frequency stability of better than ± 4 MHz from −30° to +60°C represent the best results reported in this frequency band. The compact packaging and low power dissipation are other attractive features of this approach. The technology used is capable of being implemented with all functions on a single GaAs MMIC chip.

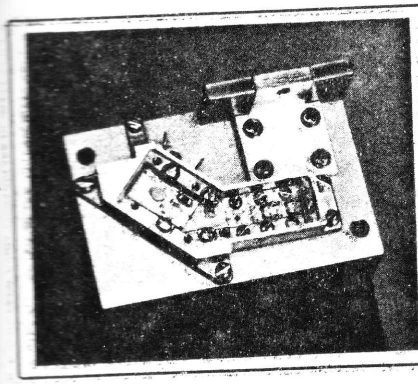

Fig. 1 A photograph of the 45 GHz source using a GaAs MESFET DRO at 22.4 GHz followed by a GaAs PHEMT frequency doubler and GaAs MESFET buffer amplifier.

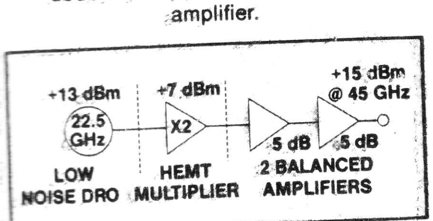

Fig. 2 A schematic diagram of the 45 GHz DRO source.

Design Approach

The 45 GHz source comprises a dielectric resonator oscillator (DRO), a frequency multiplier and an amplifier, as shown in Figure 2. The DRO uses a low noise 0.3 μm GaAs MESFET with a gate width of 600 μm, and consists of a multifeed T gate geometry layout to minimize the gate-metal resistance. The device is fabricated with high quality vapor phase epitaxial material using AuGe/Ni/Au as the contact metal, double recesses and refractory metal in the gate step, and silicon nitride in the device passivation layer. The F_t and F_{max} estimated from the S-parameters of typical devices measured at up to 26.5 GHz are 40 GHz and 80 GHz, respectively. The dielectric resonator has a dielectric constant of 29 and a temperature coefficient of 6 ppm/°C. The measured unloaded Q of the resonator is 2150 at 22.5 GHz.

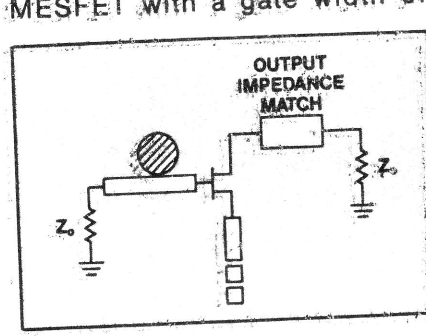

Fig. 3 The DRO is a GaAs MESFET oscillator using capacitive series feedback at the source terminal to generate negative resistance at the FET gate.

The series feedback oscillator, shown in Figure 3, was designed with conventional linear techniques employing S-parameters. Using commercially available linear CAD software, the combination of capacitive series feedback at the source terminal and an open stub at the drain terminal was found to generate the appropriate negative resistance at the FET gate. Figure 4 shows S-parameters of the active two-port device including the series feedback and the drain stub over 20 to 25 GHz. The S_{11} at the gate is 1.3 $\angle -147°$ and the stability factor K is 0.58. The position of the dielectric resonator is now determined to satisfy the necessary oscillation condition $|S_{11}|\,|\Gamma_1| > 1$ and $\mathrm{Arg}S_{11} + \mathrm{Arg}\,\Gamma_1 = 0$.

Optimization of phase noise performance calls for the use of a

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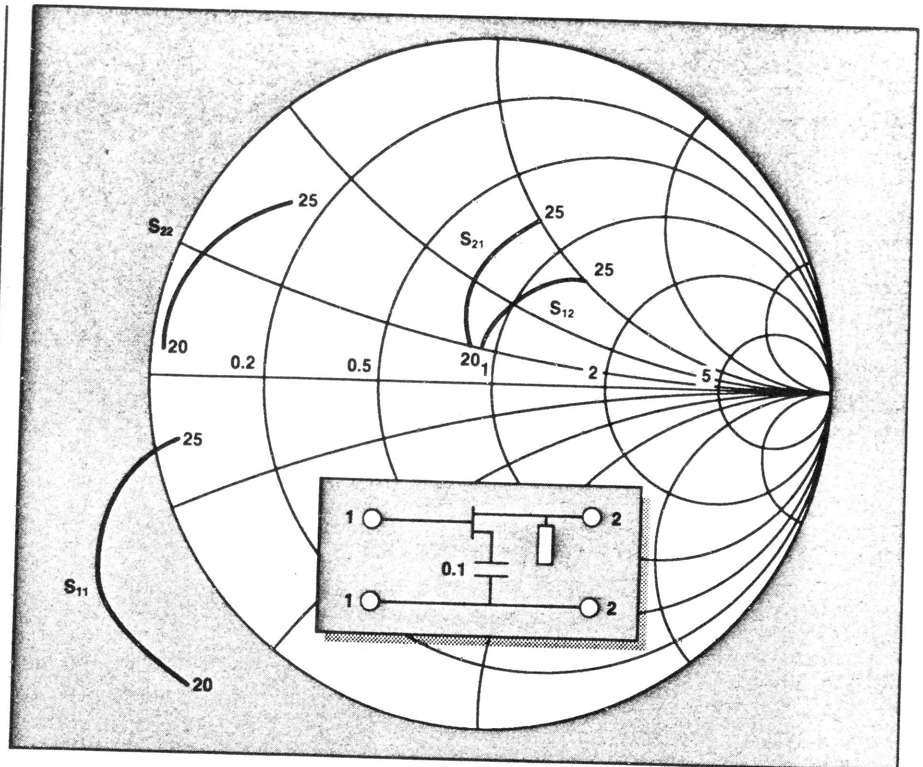

Fig. 4 The S-parameters of the active two-port, including the device and the series feedback over the 20 to 25 GHz frequency range.

TABLE I DRO ELECTRICAL CHARACTERISTICS	
Frequency (GHz)	22.4
Power output (dBm)	13
Frequency pulling (MHz) into all phases of 2 SWR	±2
Phase noise (dBc/Hz) (10 kHz from carrier)	-88
Frequency stability (MHz) (-30°C to +60°C)	±2

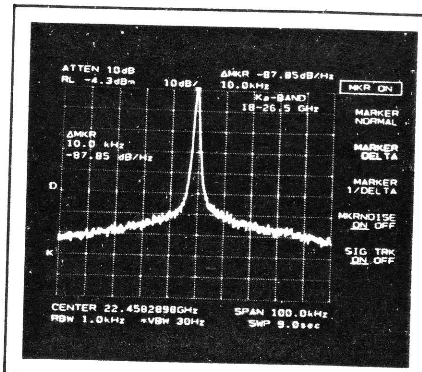

Fig. 5 A spectrum analyzer output of the 22.4 GHz oscillator.

high-Q dielectric resonator and a low noise device combined with specific considerations in the oscillator circuit. The device was selected for low 1/f noise. It is known that the low frequency noise in a GaAs FET is inversely proportional to the gate length and width of the device. The biasing conditions and the device processing also play vital roles in achieving low noise oscillators. The dielectric resonator coupling to the transmission line was calculated to optimize the loaded Q of the resonator, oscillator power output and temperature stability.[1] The important test parameters of the oscillator realized are described in Table 1.

Figure 5 shows the spectrum of the 22.5 GHz oscillator. This represents 6 to 8 dB improvement in phase noise over typical commercial GaAs MESFET DROs.

Frequency Multiplier

The frequency multiplier uses a GaAs pseudormorphic HEMT (PHEMT) with a sub 0.2 μm gate length and 250 μm gate width, fabricated on MBE material.[2] The gates are defined using electron-beam lithography resulting in gate lengths ranging from 0.2 to 0.25 μm. This device has an F_t of 80 GHz, F_{max} of 160 GHz and is capable of delivering +17 dBm of linear power with 8 dB of gain at 18 GHz. Its main static characteristics are shown in Figure 6. The device has a high nonlinear transconductance that is ade-

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quate for harmonic generation.[3] Currently available nonlinear models are not capable of representing the nonlinear characteristics of this type of device accurately, which means that the design has to rely on experimental results. For comparison, an investigation was carried out on a multiplier test circuit operating in the 6 to 12 GHz frequency range and the results using the PHEMT were compared to those from a typical MESFET of similar surface area. The experiments showed that the PHEMT biased at $V_{GS} = -1.2$ V and $V_{DS} = 5$ V produced a multiplication gain of 9 dB and an output power of +13 dBm. This multiplication gain is 1 dB greater and has a second-harmonic output more than 4 dB higher than that produced by the equivalent MESFET multiplier.

The multiplier prototype operating at frequencies from 22.5 GHz to 45 GHz was constructed on an alumina substrate, employing the same bias conditions used in the 6 GHz circuit. An open stub of electrical length of 90° at 22.5 GHz was connected to the drain for blocking the fundamental frequency mode while simultaneously presenting the necessary drain reactance for maximum gain. The capacitance input impedance was inductively matched by means of wire bonds as shown in Figure 7. Results for the mm-wave doubler are shown in Table 2. These results were obtained over the temperature range from −30° to +60°C and confirm the adequacy of PHEMTs as mm-wave frequency multipliers.

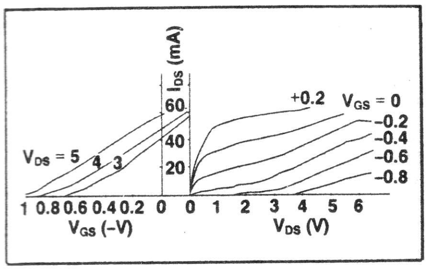

Fig. 6 Static characteristics of the GaAs HEMT used as the frequency doubler; note the high nonlinear transconductance, good for harmonic generation.[3]

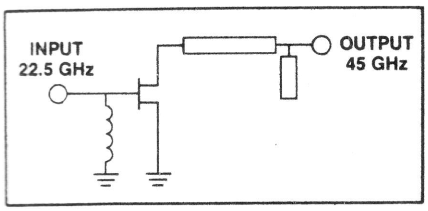

Fig. 7 A schematic diagram of the frequency multiplier. A 90° open stub at 22.4 GHz at the drain blocks the 22.4 GHz fundamental and provides the drain reactance necessary for maximum gain. The capacitive input impedance is matched inductively by means of wire bonds.

TABLE II
PHEMT MULTIPLIER CHARACTERISTICS

Frequency input (GHz)	22.4
Frequency output (GHz)	45
Input RF power (dBm)	+13
Output RF power (dBm)	
@ 45 GHz	+7
@ 22.4 GHz	−10

GaAs MESFET Amplifier

The amplifier section uses two balanced amplifiers using GaAs MESFETs.[4] The FET is a 0.2 μm

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gate length by 75 μm width device defined by optical photolithography and fabricated with VPE. The geometry uses a multifeed T gate layout with the two small side gate pads connected to the central gate bonding pad by an air bridge. This air bridge shunts the gate strip of the FET to reduce RF signal phase delay along the stripe. Since the unit gate width is thereby reduced to 12.5 μm, the gate metal resistance becomes negligible.

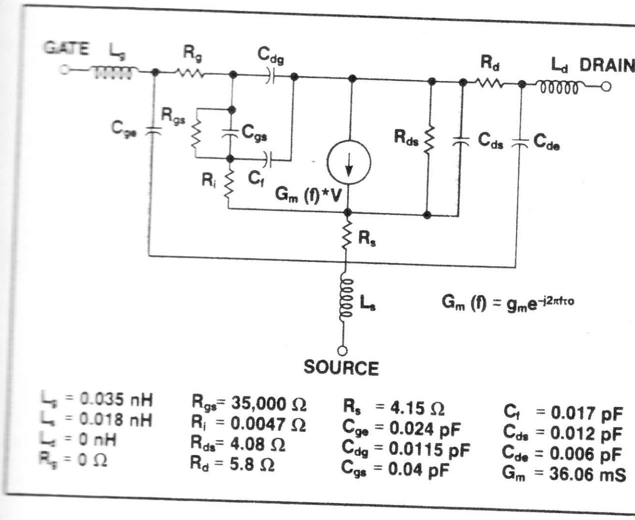

Fig. 8 A schematic diagram of the FET model used in the balanced amplifier stages. The FET is a 0.2 μm gate length by 75 μm width device with a multifeed T gate layout using airbridges between the gates and bonding pads. Source-to-drain spacing is 3.5 μm and source-to-gate spacing is 1 μm.

The T gate also minimizes feedback capacitance. The design uses a source-to-drain spacing of 3.5 μm and a source-to-gate spacing of 1 μm. The contact pads are approximately 45 μm in diameter to make bonding easy. The source-to-drain geometries are designed to ensure that all current densities remain below the electromigration limit of 6×10^5 A/cm^2 when the device is biased at saturation. The device model is shown in Figure 8.

The three-element input matching topology for the amplifier consists of a shunt-L, transmission line and shunt-C combination, shown in Figure 9. The circuit model was constructed by choosing realizable values of the matching elements and by carefully considering the effects of the circuit parasitics. The model predicted 6.5 dB gain at 45 GHz and an SWR lower than 2 at the input over the required 4 percent bandwidth.

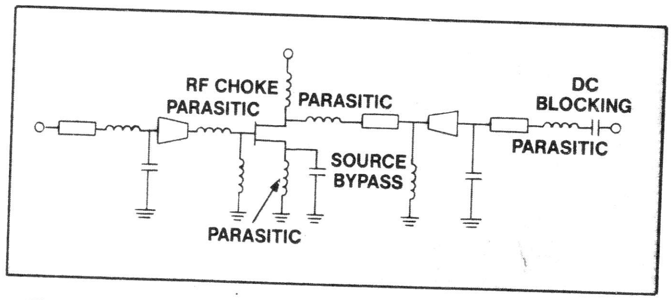

Fig. 9 The input and output matching topology for the amplifier consisting of a shunt-L, transmission line and shunt-C combination.

TABLE III PERFORMANCE OF THE 45 GHz SOURCE	
Frequency input (GHz)	44.810
Power output (dBm)	+15
Frequency pushing (MHz/V)	<0.1
Frequency drift (MHz) (−30° to +60°C)	3.7
Phase noise (dBc/Hz) (10 kHz from carrier)	−82
Bias supply	12 VDC, 175 mA

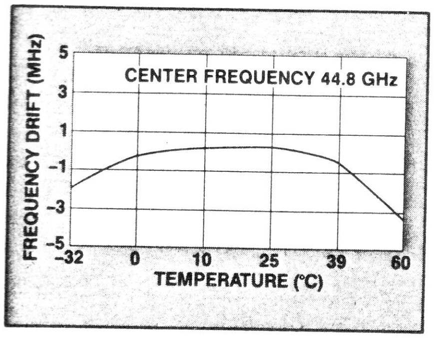

Fig. 10 Frequency vs. temperature for the 45 GHz source.

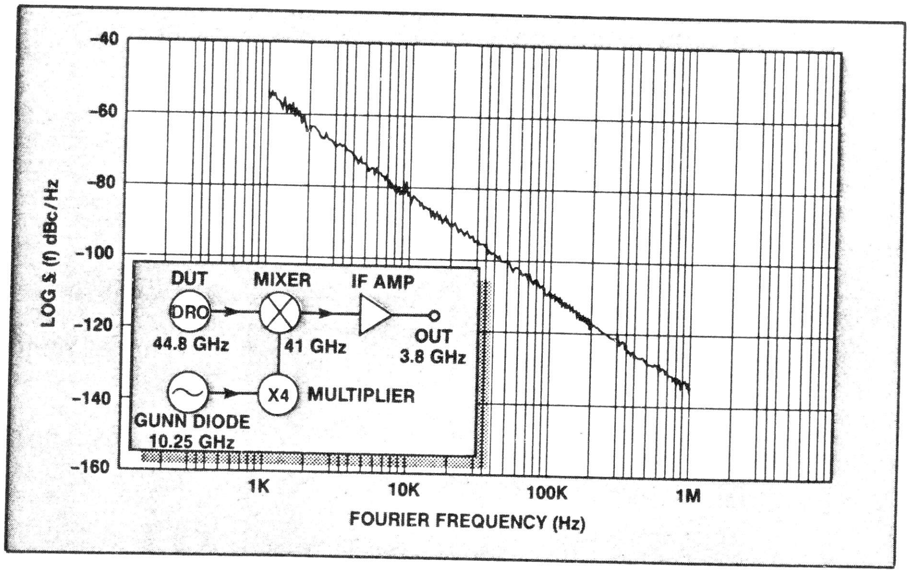

Fig. 11 Phase noise of the 45 GHz source.

Similar matching topology is used at the amplifier output. Measurements on a single-ended stage showed 7.3 dB of gain with input and output SWR of less than 2.3. A balanced pair of these amplifier stages is fabricated on a 3.3 mm × 4.95 mm alumina substrate of 0.254 mm thickness using Lange couplers. Two of these individual gain modules then are mounted on a single Kovar carrier to produce the amplifier cascade. Typical performance is 9 to 10 dB of gain, with an input power of +5 dBm, and an SWR of less than 2 at the input and output ports. The amplifier operates from a single regulated +8 V DC power supply and consumes 0.96 W of DC power.

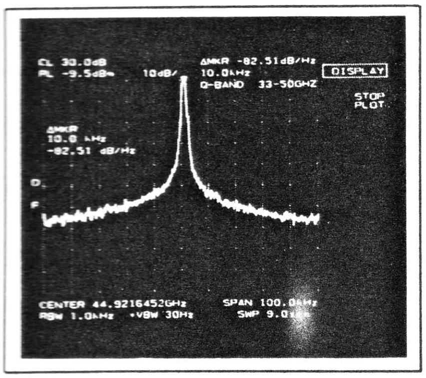

Fig. 12 Output spectrum of the 45 GHz source.

Experimental Results with the mm-Wave Assembly

The oscillator, multiplier and amplifier are constructed on 0.254 mm thick alumina substrates with thin-film hybrid circuitry, and are housed in a compact package measuring 50 mm × 50 mm × 7 mm. The output is connected to the WR22 waveguide with a feedthrough. Experimental results for the 45 GHz source operating at 25°C are listed in Table 3.

The frequency stability as a function of temperature is represented in Figure 10. The phase noise was measured after downconverting the 45 GHz signal to 3.8 GHz using a cavity stabilized Gunn source as the reference source at 10 GHz. The results are plotted in Figure 11. Figure 12 shows the output spectrum of the complete oscillator and multiplier assembly.

Conclusion

This paper has presented an oscillator design that confirms the validity of a particular approach for obtaining low phase noise. Also presented are the results of investigations of the nonlinear characteristics of PHEMTs and the application of PHEMTs as highly efficient harmonic generators. This paper also explored the capability of three different state-of-the-art microwave transistors, namely 0.3 μm × 600 μm^2 and 0.2 μm × 75 μm^2 GaAs MESFETs and a 0.2 μm × 250 μm^2 GaAs PHEMT to develop a new low phase noise, highly stable and medium power 45 GHz source.

Acknowledgment

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