High-Performance GaAs MMIC Oscillators

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Abstract —A number of monolithic single-ended and push–pull oscillator chips were developed for C-band through K_u-band applications. The chips were used to build both dielectric resonator oscillators (DRO's) and voltage-controlled oscillators (VCO's) in these frequency bands. These MMIC's also have an integrated buffer amplifier at the oscillator output to provide better load isolation and power output stability. The oscillators demonstrated performance similar to conventional hybrid circuitry; however, the MMIC circuits provide circuit simplicity with improved reliability, decreased size, and reduced manufacturing cost.

I. MMIC Circuit Description

PREVIOUS WORK on monolithic VCO's has shown excellent performance over the 2–18 GHz band [1]. The oscillator chips reported in this work all consist of a negative resistance oscillator stage with an additional buffer amplifier stage on one monolithic die. Three MMIC oscillator chips will be discussed in this paper: a single-ended C-band chip, a single-ended X-band chip, and a K_u-band push–pull chip. All chips have an identical block diagram, shown in Fig. 1. Each MMIC chip contains an oscillator, an amplifier, and all associated bias circuitry.

This circuit topology offers several advantages. A negative-resistance oscillator can be used in several different kinds of oscillators, including DRO's, YIG's and VCO's. The only part required externally to the MMIC to form an oscillator is the resonator. The incorporation of the buffer amplifier isolates the resonator from the load and minimizes the effects of frequency pulling. The buffer amplifier stage also operates in saturation, which provides constant output power and minimizes output power variation with temperature.

The oscillator circuits consist of a common source oscillator stage with a capacitive reactance in the source leg of the circuit. A simplified schematic of the oscillator chip is given in Fig. 2. The reactance on the source leg provides feedback through the internal C_{gs} of the FET to create the required negative resistance over a broad frequency range of greater than octave bandwidths.

A novel biasing scheme was used in the C-band and K_u-band oscillator chips which minimizes the bias current required by the MMIC. Only 20 to 35 mA of dc current is required to supply both the oscillator and the buffer amplifier. Each stage is also set up to act as active load for the other stage, setting the dc voltage and current bias levels for each stage. With an 8-V dc bias, the C-band oscillator provides +13 dBm of RF output power while drawing only 19 mA dc bias.

The amplifier stage is a conventional common source amplifier stage, as shown in Fig. 2. Some feedback was added from the drain to the gate of the amplifier to improve the output VSWR over the required bandwidth. The amount of feedback was kept to a minimum to keep the saturated output power of the amplifier as high as possible.

The saturated output power of the amplifier is fairly constant over temperature, which keeps the oscillator's output power within ±1 dB over the −54 to +85°C temperature range, in most cases. The reverse isolation to the resonator was measured at −25 to −30 dB for these chips, which provides the excellent frequency pulling figures for the final oscillators. Although the buffer stage is operating in saturation, the second harmonic levels for the oscillators are still maintained below −20 dBc.

The MMIC was designed for maximum yields. Only high-yield components such as implanted FET's, implanted resistors, and small MIM capacitors were used. The implanted FET's have 0.5 μm gate lengths and widths between 300 μm and 500 μm. The metallization is in two layers, with a first metal layer and an air bridge metallization layer above the first metal. The circuit completely avoided the use of yield-degrading elements such as via holes. The size of the MMIC die was kept to a minimum, to maximize the number of dies produced on a wafer. The C-band and X-band circuits measured 0.9×0.9 mm, while the K_u-band circuit measured 1.2×1.2 mm. With these die sizes, between 3000 and 5000 dies are produced on a 3-in wafer.

Because the use of via holes was avoided, the K_u-band oscillator chip was designed using a balanced or push–pull configuration. In this configuration, the circuit is duplicated in a "mirror image." Each side of the circuit operates 180° out of phase with respect to the other side of the circuit, so a virtual ground is formed along the center line of the circuit. The signals at the outputs are combined through a balun for interface to an unbalanced output transmission line. The virtual ground forms the needed RF ground along the center line of the MMIC. The virtual ground is on the top of the die, eliminating the need to use via holes to form short RF grounds in the center of the die. This is especially important at higher frequencies such as K_u-band, where minimum inductance to ground is required for maximum gain and maximum bandwidth. Because this problem is not as critical at lower frequencies, a

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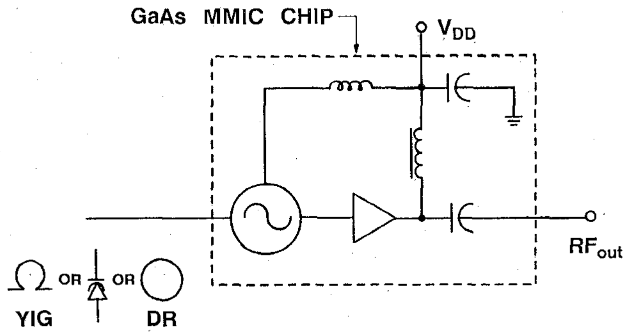

Fig. 1. Block diagram of the GaAs MMIC negative-resistance oscillator chips.

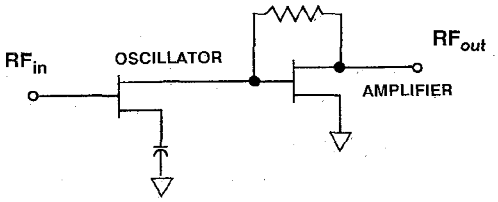

Fig. 2. Simplified schematic diagram of the negative-resistance oscillator stage and the feedback buffer amplifier.

conventional single-ended scheme without via holes was used on the *C*-band and *X*-band chips.

The resonator element is the only element required externally to the MMIC to form an oscillator. The nonintegration of the resonator provides flexiility in the application of the chip. Very high *Q* external resonator elements can be used with the MMIC, such as dielectric resonators for DRO's, varactor diodes for VCO's, or YIG spheres for YIG tuned oscillators. These elements are connected to the negative-resistance terminal of the MMIC in such a way that RF power is reflected back to the MMIC at resonance with the proper phse angle to produce the required 180° phase shift to support oscillations.

II. *C*-Band Oscillators

The *C*-band oscillator chip used a single-ended design scheme for both the oscillator and the amplifier. Fig. 3 is a photograph of the *C*-band MMIC die. This chip was used to build both a VCO and a DRO.

The VCO was realized by connecting a varactor diode to the negative-resistance pad of the MMIC. A series resonant circuit was formed between the bond wire inductor and the varactor. A hybrid circuit was built using MIC techniques to assemble and package the VCO. Fig. 4 is a photograph of this hybrid circuit, which is a complete VCO in a transistor package. This part contains an internal voltage regulator and measures 0.525 in $\times$ 0.525 in.

The VCO tunes from 3.6 to 5.9 GHz with 0 to 20 V of tuning voltage. The output power is $+12.5$ dBm with ± 0.75 dB flatness over the tuning range, with the second harmonic below -20 dBc. The dc bias requirement is $+8$ V dc at 19 mA dc. Fig. 5 presents the tuning and power curve for the oscillator.

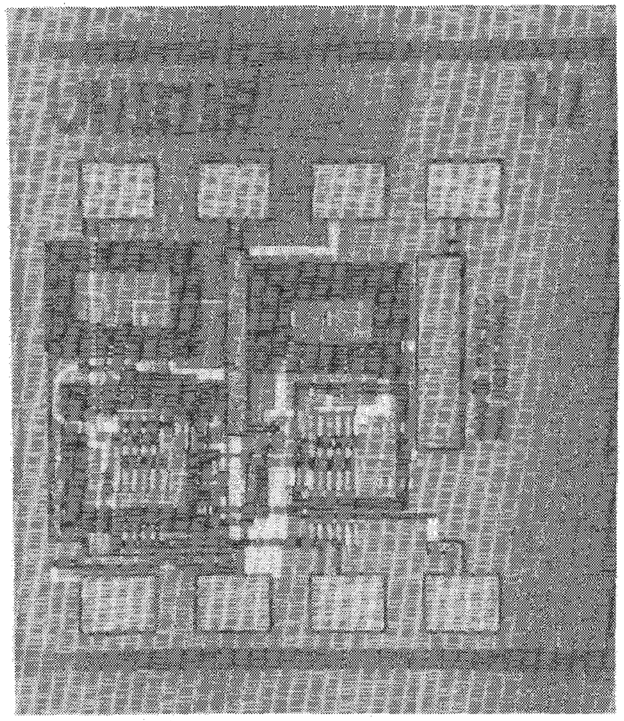

Fig. 3. Photograph of the *C*-band MMIC oscillator die.

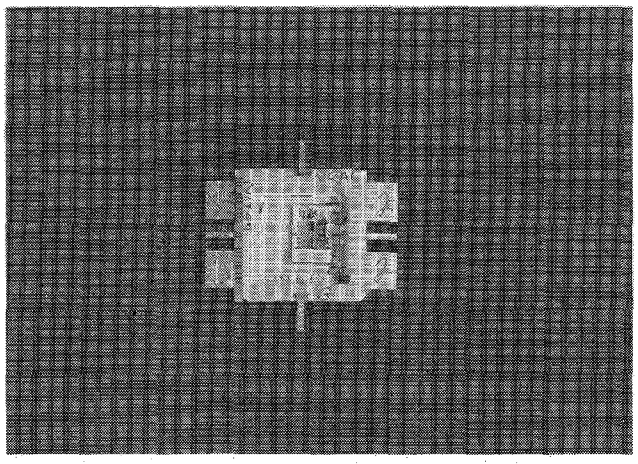

Fig. 4. Complete *C*-band VCO in transistor package using the MMIC oscillator chip and a varactor diode.

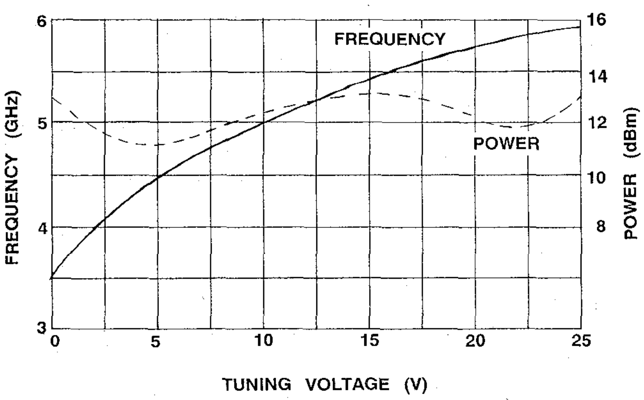

Fig. 5. Tuning curves for the *C*-band MMIC VCO.

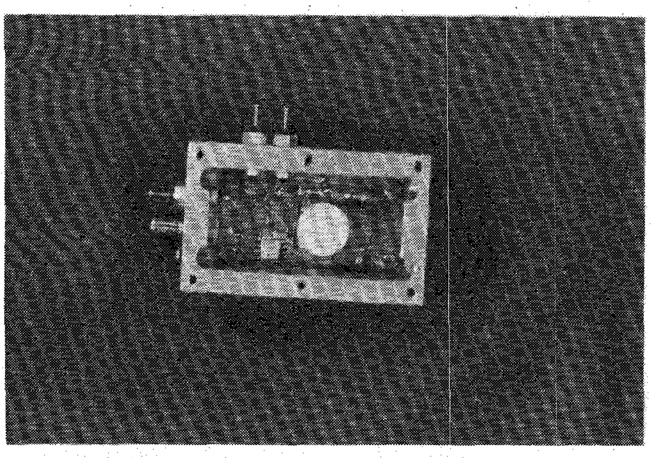

Fig. 6. Photograph of the *C*-band DRO using a packaged MMIC die and soft-board assembly techniques.

TABLE I
SUMMARY OF MMIC DRO PERFORMANCE

Parameter	Frequency Band C-band	X-band	Ku-band	Units
Frequency	5.027	10.740	13.120	GHz
Output Power	+12	+16	+10	dBm
SSB Phase Noise:				
100 k Hz	-115	-110	-100	dBc/Hz
10 kHz	-88	-80	-70	dBc/Hz
Frequency Pulling	.02	.02	.001	% (3:1 VSWR)
Bias Voltage	8	4	11	Volts
Bias Current	19	65	35	mA
Stability measured from -54 to +85 °C				
Freq Stability	±2	±4	±5	ppm/°C
Power Stability	±0.75	±1.0	±0.5	dB

A 5-GHz DRO was also constructed using a packaged MMIC chip. This DRO was built with the MMIC inserted in a hermetic package, which was then assembled on a soft board substrate [2]. A photograph of the DRO is shown in Fig. 6. The large size of the final oscillator is determined by the size of the dielectric resonator; however, some size reduction is realized for the final oscillator because the buffer amplifier is incorporated in the MMIC die, eliminating the space required for a hybrid amplifier, as with the discrete oscillator approach.

The DRO shows exceptional RF performance with good spectral purity. The electrical performance of the DRO is summarized in Table I, along with the performance of the DRO's in the other frequency bands. The low phase noise level for the *C*-band DRO is obtained because of the high level of input reflection gain (+8 dB), which corresponds to a large negative resistance. The high gain allows the dielectric resonator to be decoupled from the microstrip coupling line, maximizing the loaded Q of the resonator [3]. The frequency pulling data are also excellent, due to the high reverse isolation provided by the buffer amplifier and the oscillator, as well as the high loaded Q of the decoupled resonator.

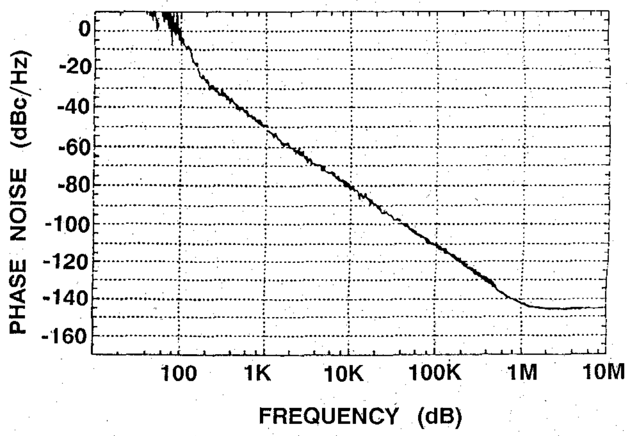

Fig. 7. Single sideband phase noise plot for the *C*-band MMIC DRO.

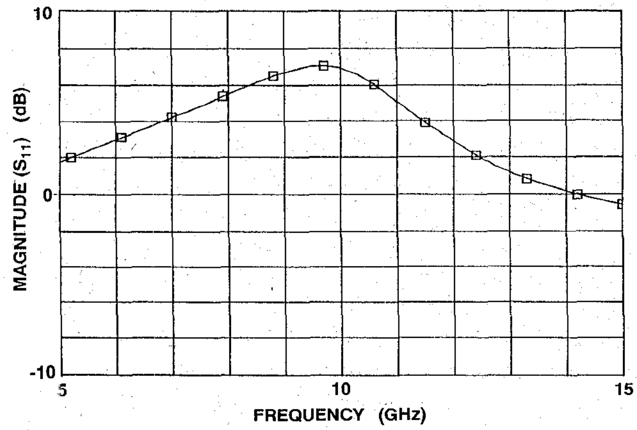

Fig. 8. Measured magnitude of negative resistance (S_{11}) as a function of frequency for the *X*-band MMIC oscillator chip.

Voltage-tuned DRO's (VTDRO) were also built using the same MMIC and similar construction by coupling a varactor diode to the dielectric resonator [4]. These oscillators operate at 5.1 GHz and are tunable by 12 MHz with a 0 to 10 V varactor voltage. More voltage tuning is available by coupling the varactor more tightly to the resonator, but single sideband (SSB) phase noise will be degraded with tighter coupling. A plot of the SSB phase noise of the 5.1-GHz VTDRO is shown in Fig. 7.

III. *X*-BAND OSCILLATORS

The *X*-band MMIC oscillator was another single-ended MMIC designed for medium power output applications. This MMIC used two 500-μm-gate-width FET's to form the oscillator and buffer amplifier. The FET's were biased at higher current levels than the other two oscillator chips to produce higher RF output power levels.

This chip has a minimum of +3 dB of input reflection gain over the 6 to 12 GHz frequency band. Fig. 8 is a plot of the measured input reflection gain (S_{11}) of the oscillator MMIC. This oscillator chip provides +16 dBm of RF output at *X*-band frequencies.

A 10.75-GHz DRO was assembled using this chip as the active element. This DRO again had very good electrical properties, with the performance summarized in Table I.

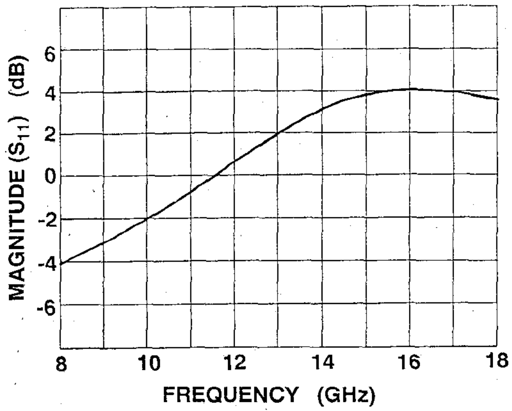

Fig. 9. Measured magnitude of negative resistance (S_{11}) as a function of frequency for the K_u-band MMIC oscillator chip.

The X-band DRO was fabricated using MIC techniques [5]. A single 50-Ω microstrip transmission line was connected to the negative-resistance pad of the MMIC. This line was about 1 in long and terminated in 50 Ω at the other end. The dielectric resonator was coupled to this line, to produce reflections back to the MMIC at the resonant frequency. The position of the resonator along the transmission line was varied experimentally until the length of the line between the MMIC and the resonator achieved the proper phase angle to support oscillations. The resonator was supported by a 0.050-in high forsterite ceramic standoff to raise the resonator above the ground plane and increase the loaded Q of the resonator.

The output of the MMIC connected directly to the 50-Ω output of the oscillator without any additional matching circuitry. The MMIC chip contained all input-matching, output-matching, and bias circuitry. This made construction of the DRO very simple.

IV. K_u-Band Oscillators

A separate MMIC oscillator was developed for operation at K_u-band frequencies. This chip uses a balanced design scheme for both the oscillator and the amplifier and shows negative resistance over the 12 to 18 GHz frequency band, with input return loss measured at +4 dB. Fig. 9 shows the measured frequency response of the input negative resistance (S_{11}). A photograph of the MMIC is shown in Fig. 10. This chip measures 1.2×1.2 mm and uses 0.5-μm-gate-length FET's with 300-μm gate widths.

A DRO operating at 13 GHz was built using this MMIC. The oscillator was assembled using MIC techniques with alumina microstrip transmission lines coupling into the dielectric resonator, similar to the X-band circuit. A photograph of the K_u-band DRO is shown in Fig. 11. The microstrip lines couple into the dielectric resonator on opposite edges to produce the required 180° phase difference between each leg of the push–pull circuit. The resonator is again suspended on a forsterite dielectric standoff to lift the resonator off the ground plane and improve the loaded Q of the resonator.

The K_u-band DRO demonstrates good RF performance with the same desirable pulling figures as were present with the other oscillators. A summary of the electrical performance of the K_u-band DRO is also given in Table I. The output power variation with temperature is very low for this circuit. This is due to the buffer amplifier operating deeply into saturation and the bias scheme which provides constant current through the GaAs FET's in the MMIC.

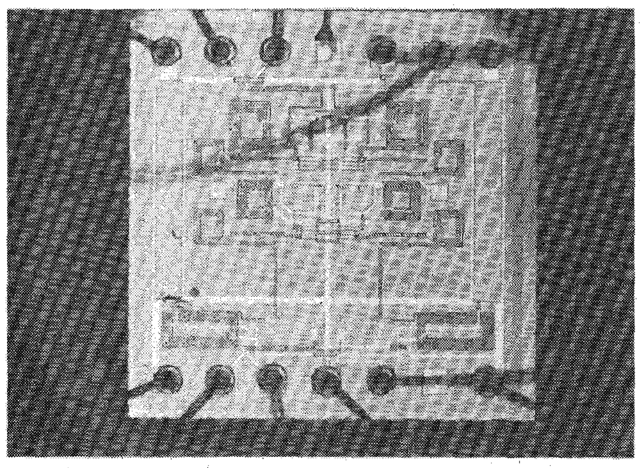

Fig. 10. Photograph of the K_u-band MMIC oscillator die.

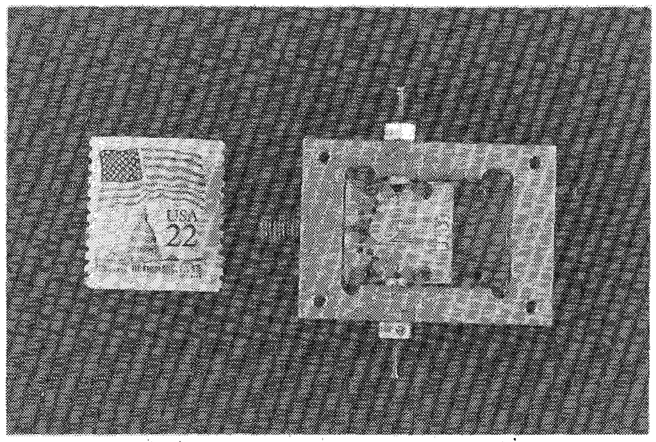

Fig. 11. Photograph of the K_u-band MMIC DRO assembled using MIC techniques. The dielectric resonator is coupled to the microstrip transmission lines for push–pull operation.

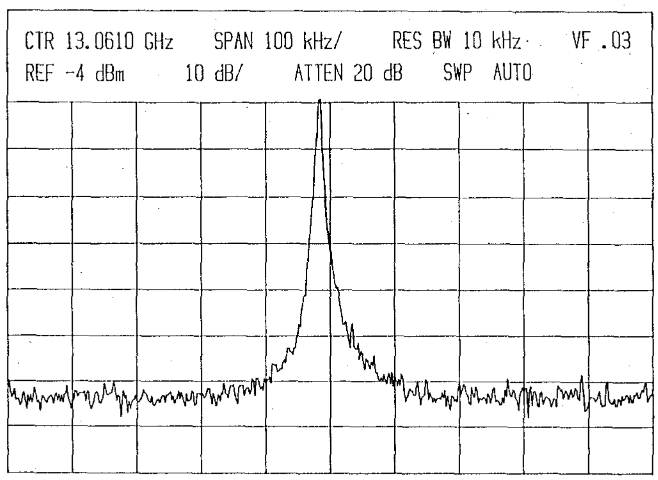

Fig. 12. Output spectrum for the push–pull K_u-band MMIC DRO.

The K_u-band DRO has good SSB noise performance, with the output spectrum shown in Fig. 12. The oscillator shows slightly degraded loaded Q from the results at C-band and X-band. This is due to the increase in frequency and the additional loss introduced from coupling two microstrip lines into the resonator.

V. Summary

GaAs MMIC technology has been demonstrated to be valuable in several microwave source applications. With MMIC oscillators designed for versatility, one die can be used to meet several applications. The small die size allows maximum flexibility in packaging. The MMIC's can be assembled in hermetic packages as small as standard transistor packages or placed directly into hybrid MIC circuits.

The integration of a buffer amplifier in addition to a basic oscillator enhances the overall performance of the oscillator. The amplifier minimizes frequency pulling and output power variation. When used in oscillator subsystems, monolithic circuits can provide several other advantages over discrete components, including reduced cost, less assembly time, a higher level of system integration, and improved reliability.

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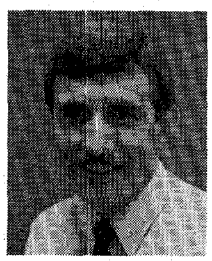

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