A Highly Stabilized GaAs FET Oscillator Using a Dielectric Resonator Feedback Circuit in 9–14 GHz

OSAMU ISHIHARA, TETSUROU MORI, HIROSHI SAWANO, AND MASAAKI NAKATANI

***Abstract*—A new type of highly stabilized GaAs FET oscillator using a dielectric resonator and a stabilization resistor in the feedback circuit has been developed. The oscillator fabricated with a microwave integrated circuit has a high external quality factor Q_{ex} of more than 1000 with no hysteresis phenomena.**

The microwave characteristics of the GaAs FET oscillator has revealed 1) high efficiency of 20 percent with 70-mW output power at 11.85 GHz, 2) a wide tuning range more than 1000 MHz, 3) a wide oscillation frequency from 9 to 14 GHz with same MIC pattern by using five dielectric resonators of different sizes, 4) a high-frequency stability as low as ±150 kHz in the temperature range from −20 to +60 °C, and 5) low FM noise of 0.07 Hz/$\sqrt{\text{Hz}}$ at off-carrier frequency of 100 kHz.

I. Introduction

With recent advances in GaAs field effect transistor (GaAs FET) and microwave integrated circuit (MIC) technology, it has become possible to realize oscillators, amplifiers, and mixers even above X band. The GaAs FET oscillator has been reported as a very attractive solid-state microwave oscillator with high-efficiency and low-operation voltage [1]–[4].

When the GaAs FET oscillator is intended to use in the satellite communication and broadcasting systems, for example in a superhigh frequency (SHF) TV receiver, a high-frequency stability against bias voltage and ambient temperature, an easy frequency tuning mechanism, and low-noise characteristics in addition to an adequate output power are required [5],[6].

Stabilized microwave oscillators using low-noise GaAs FET's have been reported by many authors [7]–[9]. James *et al.* obtained stabilized GaAs FET oscillators in an 11-GHz band using a resonant cavity as either a transmission filter or an external feedback circuit [7]. Abe *et al.* reported a 6-GHz stabilized GaAs FET oscillator using a dielectric resonator as a band rejection filter [8]. Recently, Saito *et al.* reported a 6-GHz GaAs FET oscillator stabilized by a dielectric resonator in an external feedback circuit [9]. These oscillators have more or less the disadvantages of large and complicated structures. Furthermore, a hysteresis phenomenon or a narrow-frequency tuning range presents difficult problems for practical use in some oscillators. Also, in a frequency range lower than X band, bipolar transistor oscillators have been stabilized with a dielectric resonator and a resistor used as a band-pass filter in the output [10] or as a feedback circuit [11].

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In this paper, we propose a new type of highly stabilized GaAs FET oscillator using a dielectric resonator and stabilization resistors in a parallel feedback circuit and describe its performances mainly based on experimental results. The oscillator provides such excellent performances as no hysteresis phenomena, a high-frequency stability against temperature, a wide-frequency tuning range, and low noise. For instance, the oscillator has a frequency stability of ±150 kHz over a temperature range from −20 to +60 °C with more than 20-mW output power and a wide mechanical frequency tuning range of over 1000 MHz, without troublesome mode jump in the frequency range from 9 to 14 GHz, by using five dielectric resonators of different sizes in same MIC pattern. Furthermore, the oscillator has a simple structure and is compactly constructed using microwave integrated circuits.

II. Fabrication of MIC Stabilized Oscillator

A. Dielectric Resonator Feedback Circuit

Microwave transistor oscillators are classified according to the oscillation mechanism into two typical types, the feedback type and the negative resistance type [12]. For the simplicity of the circuit design, we adopted a feedback type, which is composed of a feedback element between the output port and the input port of the microwave transistor amplifiers.

Microwave transistor oscillators are usually fabricated with microwave integrated circuits and the feedback elements are constructed with microstrip lines, [13] a microstrip resonator [7] or lead wires with a chip capacitor [14]. However, such simple elements have two weak points. One is the difficulty in forming a high-Q resonator. Another is the inflexibility of the electrical performances such as feedback power or frequency.

On the other hand, a dielectric resonator has advantages of small size and easy frequency tuning. An improvement in the quality factor Q and temperature coefficients have been realized by recent ceramic technology [15]–[17]. Therefore, we have attempted to use the dielectric resonator as a feedback circuit of a GaAs FET oscillator.

Fig. 1 shows a basic configuration of the dielectric resonator feedback circuit proposed in this paper. As

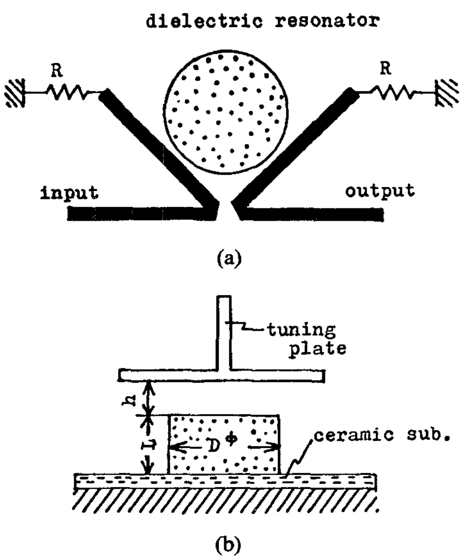


Fig. 1. (a) Feedback circuit using a dielectric resonator and stabilization resistors. (b) Cross section of a dielectric resonator feedback circuit.

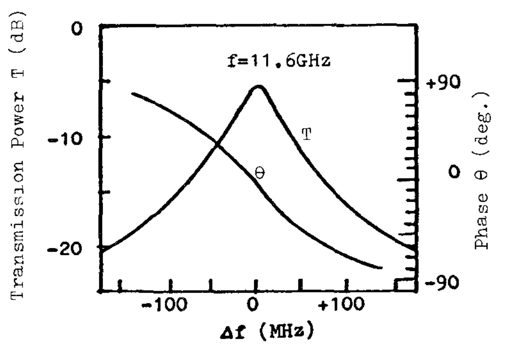


Fig. 2. Transmission characteristics of a feedback circuit.

shown in Fig. 1, the circuit is fabricated on an alumina substrate and composed of a dielectric resonator placed between two perpendicular microstrip lines terminated with resistors having characteristic impedance R. The two microstrip lines are magnetically coupled through the cylindrical dielectric resonator of the $TE_{01\delta}$ mode. The transmission frequency of the filter can easily be changed by adjusting an air-gap spacing h between the dielectric resonator and the frequency tuning plate in Fig. 1(b). The feature of this filter is that there is little power reflection at the input and the output terminal because of the stabilization resistor R. Therefore, the oscillator does not show hysteresis phenomenon.

Fig. 2 shows an example of the transmission characteristics of this filter. The transmission power T and phase θ are depicted as a function of frequency deviation, where the center frequency is 11.6 GHz. In this filter, the dielectric resonator is 5.5 mm in diameter and 1.8 mm in thickness and the characteristic impedance of the microstrip line is 50 Ω. The transmission power at the center frequency is about 5 dB which is large enough to build a feedback circuit in the GaAs FET oscillator, because the power gain of the GaAs FET amplifier is usually larger than 5 dB in X to Ku band [18], [19]. The quality factor of the MIC bandpass filter is about 1000 as shown in Fig. 2, though the Q of the dielectric resonator is slightly higher than 4500 at 11.6 GHz. This is because the dielectric resonator is directly placed on the alumina ceramic.

The transmission power T and phase θ can also be adjusted by changing the distance between the dielectric resonator and the microstrip lines. This feasibility is useful for fabricating the GaAs FET oscillator, since the high-frequency parameters are often scattered from device to device.

B. MIC GaAs FET Oscillator

When the filter using the dielectric resonator and the resistors shown in Fig. 1 is applied to the drain-to-gate feedback circuit of the FET amplifier, a highly stabilized GaAs FET oscillator can be obtained. Since this new type of oscillator has a dielectric resonator feedback circuit, we named this oscillator DRF GaAs FET oscillator.

Fig. 3 shows photographs and schematically drawn MIC patterns of the several DRF GaAs FET oscillators, which are fabricated with the microstrip lines on the alumina ceramic substrate. In these oscillators, microwave power is incident on the gate terminal, and then the amplified power out of the drain terminal is fed back through the dielectric resonator to the gate terminal. The two microstrip lines of the drain and the gate are coupled magnetically through the cylindrical dielectric resonator. The angle of the lines are experimentally arranged at a right angle to obtain a large amount of the output power. By the same reason, the characteristic impedances of the drain and the gate lines are 40 Ω and 50 Ω, respectively.

The output power is taken out from the source terminal as shown in Fig. 3(a) and 3(c), or from the drain terminal in Fig. 3(b). The source output configuration is preferable for operation with a single power supply because a capacitor floating the GaAs FET from the ground could be eliminated. On the other hand, the drain output configuration is preferable for high-power GaAs FET oscillator because the package of the power FET is especially constructed considering heat dissipation and it is difficult to obtain the microwave power at the source terminal. In this experiment, the characteristic impedance of the microstrip line is designed to be 30 Ω and the matching circuit between the GaAs FET and 50 Ω load R_L consists of a tapered microstrip line. The source terminal is floated from the ground by using a dc block composed of coupled microstrip lines.

The microstrip lines connected to the drain and the gate are terminated with resistors of the corresponding characteristic impedance of the lines as shown in Fig. 3(a) and 3(b). In these oscillators, the feedback from the drain to the gate is formed at the resonant frequency of the dielectric resonator and the microwave power is generated only at the frequency. At the nonresonant frequency, the gate and the drain are both pure resistive and no microwave oscillation attributable to the lengths of the microstrip lines occur. As is later described as the experimental results, this type of oscillator has no mode jump or hys-

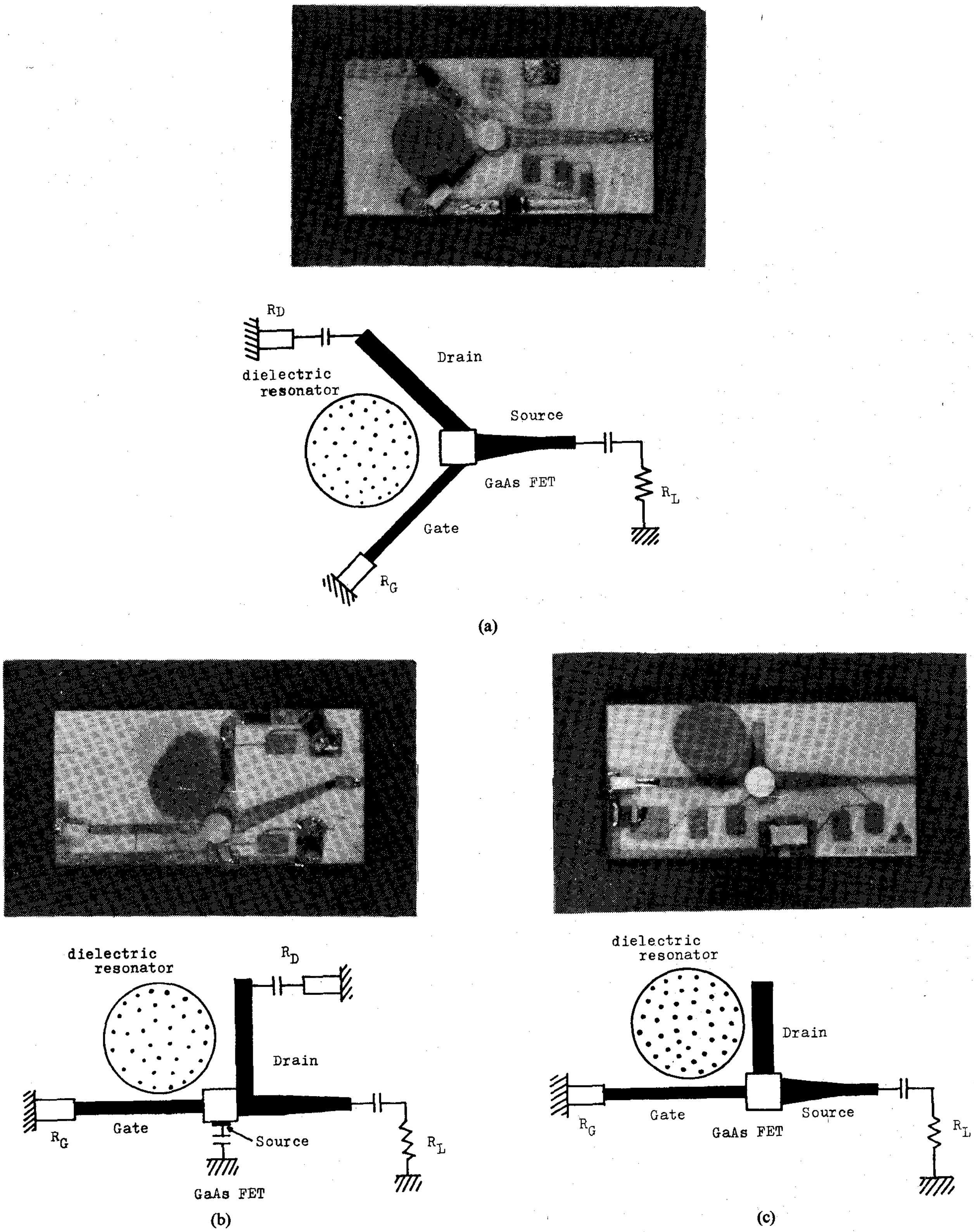


Fig. 3. Photographs and schematically drawn MIC patterns of the several DRF GaAs FET oscillators. (a) Source output type. (b) Drain output type. (c) Source output type with only a gate resistor.

teresis which was observed in the oscillator with a dielectric resonator [8]. In fact, when the gate resistor was omitted in order to ascertain the effect of the terminal resistor, the spurious oscillation depending on the length of the gate microstrip line was observed. On the other hand, when the drain resistor was omitted, the spurious oscillation was not observed. On the basis of these experiments, we have recognized that the oscillator with only a gate resistor, as shown in Fig. 2(c), is the simplest configuration for practical application. In this case, the drain

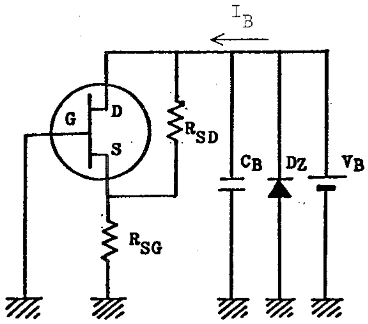
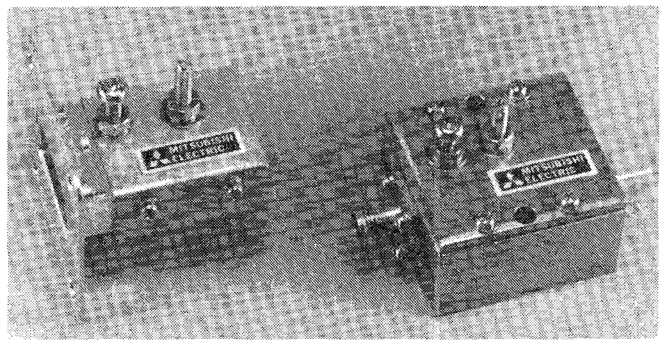


Fig. 4. Bias circuit of an oscillator operated by a single dc power supply.



(a) (b)

Fig. 5. Photographs of DRF GaAs FET oscillators. (a) With a BRJ-120 waveguide flange. (b) With a SMA-J coaxial connector.

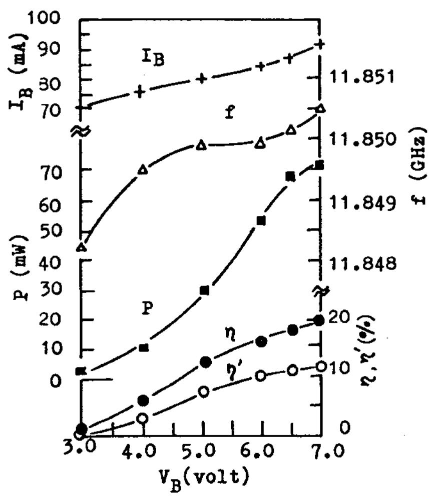


Fig. 6. Oscillation characteristics of DRF GaAs FET oscillator as a function of bias voltage.

line from the open end to the point of contact with the resonator is designed to be 1/4 wavelength so that the resonator may strongly be coupled with the drain line [20].

The MIC DRF GaAs FET oscillator is fabricated using a Au/Cr metallized alumina ceramic substrate of 12.7-mm width, 25.4-mm length, and 0.635-mm thickness. The microstrip circuit pattern is formed with an ordinary photolithographical technique. A low-noise GaAs FET chip, chip capacitors, and chip resistors are soldered onto the MIC pattern.

The GaAs FET used in the oscillator is a small-signal MESFET, MGF-C-1400, with an Al gate 0.7 μm long and 400 μm wide [18]. The chip has a drain saturation current of 70–100 mA and a transconductance ranging 45–55 mS. Examples of the microwave performance are linear gain of 8 dB and output power of 90 mW at 1-dB gain compression at 12 GHz.

The feedback circuit is a MIC bandpass filter formed by a cylindrical dielectric resonator which is made of a low-loss dielectrical material, SnO_2–TiO_2–ZrO system, with a dielectric constant of 37.5. The quality factor Q is higher than 4500 at 11.6 GHz. The dielectric resonator with resonant frequency temperature coefficient of 4 PPM/°C in free space was selected in consideration of thermal expansion of metal case. The diameter and the thickness of the dielectric resonator are determined according to oscillation frequency concerned, which is nearly equal to the resonant frequency.

C. Bias Circuit

In addition to the RF circuit of the oscillator, the dc bias circuit also plays an important role in the achievement of the superior performance of the oscillator. The GaAs FET usually operates with two bias voltages of different polarities, positive bias for drain and negative bias for gate, resulting in the requirement of two dc power supplies. However, operation with a single power supply is preferable for applications such as local oscillator in SHF TV receiver systems. Therefore, we investigated the microwave performance of the FET oscillator with a bias circuit operated by a single power supply as shown in Fig. 4.

The gate terminal is grounded and the source–gate voltage V_{SG} is determined by the resistance R_{SG} ranging from 10 to 15 Ω and the bias current ranging from 50 to 100 mA. The drain current I_D is adjusted to about half the drain saturation current. The resistance R_{SD} from 200 to 300 Ω is inserted in order to suppress the fluctuation of the voltage V_{SG} caused by ambient temperature variation. The capacitance C_B about 4000 pF reduces some noise through bias feeders and Zenor diode D_Z prevents the drain bias voltage from exceeding the absolute maximum rating of the GaAs FET.

D. Case Construction

Fig. 5 shows photographs of the cased GaAs FET oscillators with a BRJ-120 waveguide flange and a SMA-J coaxial connector. For the type of waveguide case, a tapered ridge waveguide is used to convert the microstrip line into WRJ-120 waveguide [20].

III. Experimental Results

A. Bias Dependence

Fig. 6 shows output power P, oscillation frequency f, device efficiency η, oscillator efficiency η', and bias current I_B as a function of bias voltage V_B. The device efficiency η is considered to be the dissipated dc power of the GaAs FET itself and the oscillator efficiency η' that of the oscillator including a bias circuit shown in Fig. 4. The

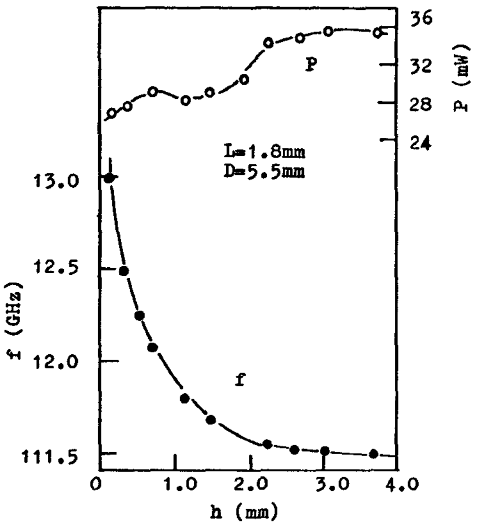


Fig. 7. Mechanical tuning characteristics as a function of air-gap thickness (h).

two kinds of efficiencies are calculated as follows:

$$\eta = \frac{P}{V_B \cdot I_B - \left\{ \left(\frac{V_B - I_B \cdot R_{SG}}{R_{SD}} \right)^2 \cdot R_{SD} + I_B^2 \cdot R_{SG} \right.}$$

$$\eta' = \frac{P}{V_B \cdot I_B}.$$

It is seen from Fig. 6 that the output power monotonously increases with bias voltage and does not saturate below 7 V. At a bias point of 7 V, the output power of 70 mW was obtained. The efficiencies η and η' also increase with bias voltage as shown in Fig. 6. At a bias point of 7 V, the device and the oscillator efficiencies are 20 percent and 12 percent, respectively.

The dependence of oscillation frequency on bias voltage is somewhat complicated as shown in Fig. 6. The oscillation frequency depends on both source to gate voltage V_{SG} and source to drain voltage V_{SD}. Increase of V_{SG} causes increase of the oscillation frequency. However, increase of V_{SD} causes decrease of the oscillation frequency. As is seen from Fig. 4, when the bias voltage V_B rises, both V_{SG} and V_{SD} increase. Therefore the complicated behavior as shown in Fig. 6 is caused for the oscillation frequency. Nearly zero and 500 kHz/V of pushing figures are obtained at 5.5 V and 6.5 V, respectively.

The bias current I_B increases with the bias voltage because of the effect of R_{SD} in Fig. 4.

B. Mechanical Tuning Performance

The oscillation frequency of the DRF GaAs FET oscillator is adjusted by changing the air gap spacing between the dielectric resonator and the frequency tuning plate in Fig. 1(b).

Fig. 7 shows mechanical tuning characteristics as a function of the air-gap spacing h. The tuning range over 1500 MHz is obtained. However, in case of narrow air gap, i.e., for higher frequency, the external quality factor

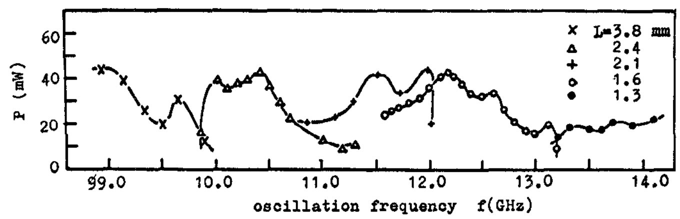


Fig. 8. Mechanical tuning characteristics with different resonator thickness (L) as a parameter.

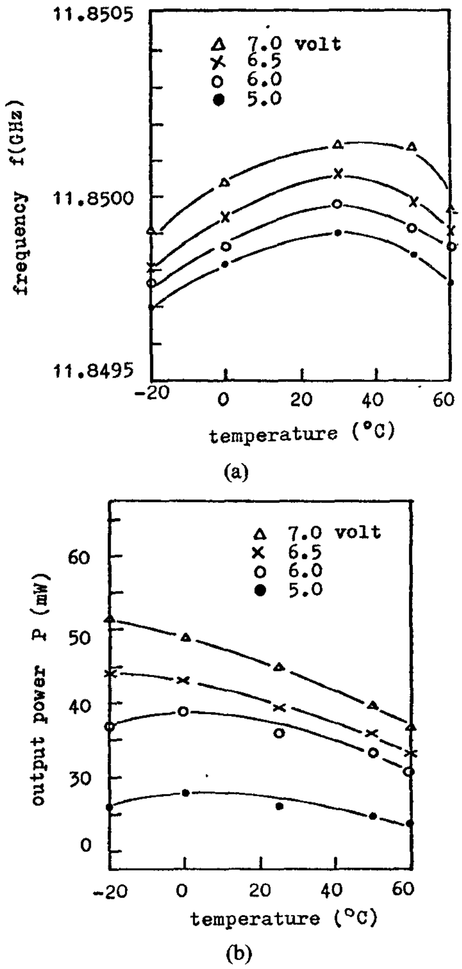


Fig. 9. (a) Oscillation frequency and (b) output power for ambient temperature from −20 to +60 °C with bias voltage as a parameter.

Q_{ex} is degraded and the practical tuning range with Q_{ex} more than 1000 is about 1000 MHz. The quality factor Q_{ex} for tuning range from 11.5 to 12.5 GHz was maintained over 1000. Furthermore, any hysteresis phenomenon is not observed over the tuning range.

Fig. 8 shows another example of the tuning characteristics of an oscillation with the same MIC pattern and GaAs FET. From this figure, it is found possible to obtain a wide oscillation range from 9 to 14 GHz with the mechanical tuning range of more than 1000 MHz by changing thickness of the dielectric resonator.

C. Temperature Performance

Fig. 9 shows the microwave performance depending on ambient temperature. The cylindrical dielectric resonator

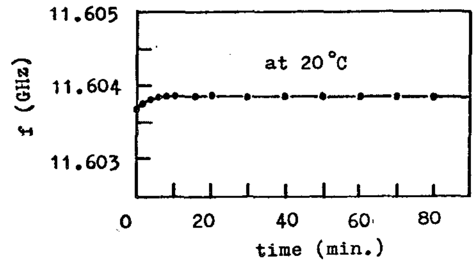


Fig. 10. Oscillator frequency as a function of time after switching on.

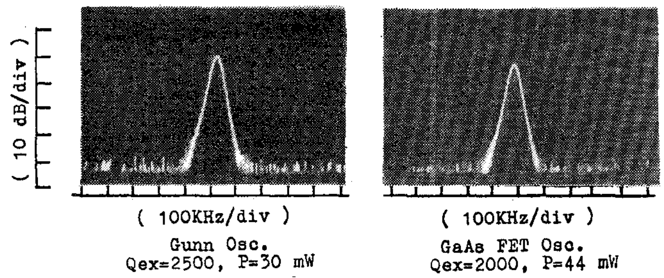


Fig. 11. Spectra of the DRF GaAs FET oscillator and Gunn diode oscillator.

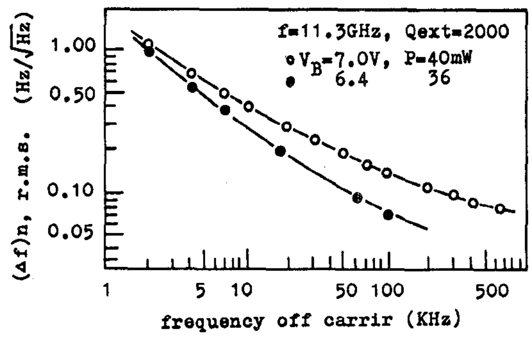


Fig. 12. FM noise of the DRF GaAs FET oscillator as a function of frequency off carrier.

5.5 mm in diameter and 1.65 mm in thickness is used. The frequency temperature coefficient of the resonator of 4.1 PPM/°C in a free space is used in consideration of the thermal expansions of the case and the tuning plate.

Fig. 9(a) shows change of the oscillation frequency f versus ambient temperature T_a ranging from -20 to $+60$ °C with bias voltage as a parameter. Frequency stability of ± 150 kHz over the temperature range between -20 and $+60$ °C or ± 0.16 PPM/°C is obtained and this value does not depend on the bias voltage as seen from Fig. 9(a). This result shows that a fine tuning of the frequency is feasible by adjusting the bias voltage, without any influences on frequency stability.

On the other hand, the temperature characteristics of the output power are depicted in Fig. 9(b) with bias voltage as a parameter. The lower bias voltage brings more stable output power and output power stability of ± 0.01 dB/°C is obtained at a bias voltage ranging from 5 to 7 V.

Though the DRF GaAs FET oscillator has the mechanical tuning range from 1000 to 1500 MHz as shown in Figs. 7 and 8, the tuning range keeping the high temperature stability described above is about 50 MHz. The main reason of this thermal stability degradation is that the frequency change depending on the ambient temperature is different for each tuning point and the thermal compensation of the oscillation frequency by only one dielectric resonator is impossible all over the tuning range. However, adjusting the frequency temperature coefficient of the dielectric resonator and the spacing between the resonator and the tuning plate, the high temperature stability described above is realized at any fixed oscillation frequency from 9 to 14 GHz.

In a practical use of a microwave oscillator, it is required that initial drift of the oscillation frequency is suppressed as small as possible. Fig. 10 shows oscillation frequency of the stabilized DRF GaAs FET oscillator as a function of the time after the start of operation. A 200-kHz frequency drift is observed in initial 4 or 5 min. However, after that, the drift is not observed at all. This initial frequency drift is not severe for practical use.

D. Spectrum and Noise

Fig. 11 shows spectra of the DRF GaAs FET oscillator and a Gunn diode oscillator for comparison at 11.6-GHz band. External quality factor Q_{ex} of the FET oscillator and that of the Gunn oscillator are 2000 and 2500, respectively. The spectrum of the FET oscillator is closely equivalent to that of the Gunn oscillator as shown in Fig. 11.

The FM noise was measured in the bias voltage range from 5 to 7 V by means of a low-noise Schottky diode and a low-loss resonant cavity. Fig. 12 shows noise characteristics as a function of off-carrier frequency for bias voltages of 7.0 and 6.4 V. At 100-kHz off-carrier frequency, the rms frequency deviation $(\Delta f)n$, rms of FM noise is 0.07 $\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ and 0.1 $\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 6.4 V and 7.0 V, respectively. It is observed that the FM noise is nearly constant for the bias voltage between 5.0 V and 6.5 V and becomes worse above 6.5 V. Though this oscillator has a wide mechanical tuning range of 1500 MHz as shown in Fig. 7, the tuning range in which the FM noise is not degraded is about 1000 MHz.

The FM noise of the DRF GaAs FET oscillator seems to be comparable to that of the Gunn diode oscillator evaluated in the same noise measurement system, and is lower than those of a GaAs IMPATT diode oscillator and another types of GaAs FET oscillators [1], [8], [21].

E. Improvement of Frequency Stability by BRF

The electrical characteristics of the DRF GaAs FET oscillator designed for 12-GHz band are listed in Table I. This performance sufficiently satisfies requirements for practical applications such as SHF TV broadcasting systems, microwave communication systems and other commercial uses.

However, sometimes, more severe performances such as higher stability, higher external quality factor Q_{ex} or excellently lower noise are required. To satisfy these requirements, it is effective to add a band rejection filter (BRF)

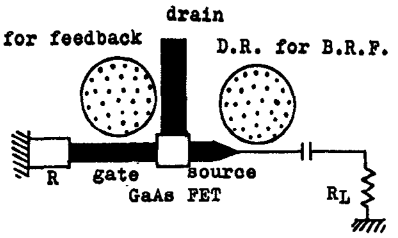


Fig. 13. MIC DRF oscillator circuit with BRF formed by a dielectric resonator.

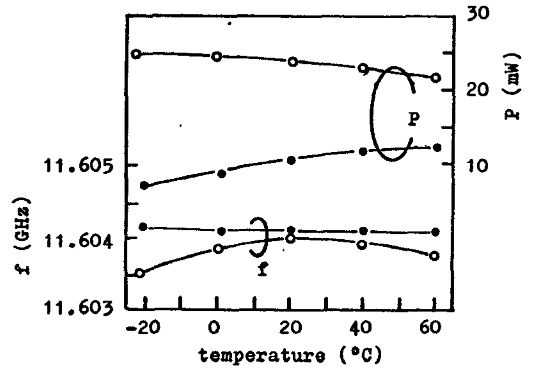


Fig. 14. Microwave performances of the original DRF FET oscillator (○) and the DRF FET oscillator with BRF (●) as a function of ambient temperature.

TABLE I
MICROWAVE CHARACTERISTICS OF THE DRF GAAS FET OSCILLATOR

bias voltage	6.5 - 7.0 volt
oscillation frequency	8.9 - 14.1 GHz
output power	70 mW
tuning range	1000-1500 MHz
efficiency	20 %
frequency stability	± 150 KHz (-20 ~ +60 °C)
pushing figure	<500 KHz
Q_{ex}	>1000
FM noise	0.07 Hz/√Hz (100 KHz off carrier)

to the DRF GaAs FET oscillator [22]. Fig. 13 shows a schematically drawn MIC circuit for a DRF GaAs FET oscillator with a BRF. The BRF consists of a dielectric resonator which is put in the vicinity of the output microstrip line. The temperature dependence of the oscillation frequency is markedly improved by introducing the BRF. The frequency deviation is reduced to ±100 kHz or less in a temperature range from −20 to +60 °C as shown in Fig. 14. The output power deviation is less than +0.022 dB/°C.

A brief explanation of the stabilization mechanism will be given by Fig. 15 which shows a relationship between resonant frequency of the BRF and oscillation frequency of the original GaAs FET oscillator (without BRF) as a function of the ambient temperature. As shown in this figure, the temperature frequency characteristics of the BRF and the original FET oscillator must be positive and

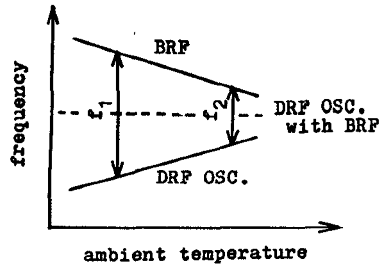


Fig. 15. Relation between oscillation frequency of the original DRF oscillator and resonant frequency of BRF.

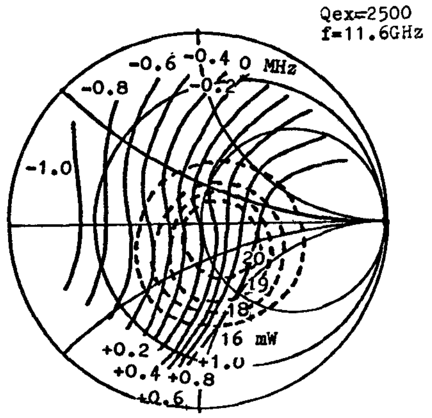


Fig. 16. Rieke diagram for a DRF GaAs FET oscillator with BRF.

negative, respectively. Besides the above condition, the oscillation frequency of the original FET oscillator must be set below the resonant frequency of the BRF. If these conditions are satisfied, the FET oscillator is locked strongly at a low temperature and the output power of the oscillator with BRF will decrease. Usually, the DRF GaAs FET oscillator generates a higher power at a low temperature. However, according to the reason described above, it is possible by using the BRF to obtain a higher power at a higher temperature as shown in Fig. 14 or a constant power over the temperature range concerned. Of course, the BRF is used as not only to control the temperature dependence of the output power but also to control the power level.

One of the most remarkable effects of the BRF is the improvement of external quality factor Q_{ex}. The Q_{ex} value of 4000 is obtained without difficulty. The high Q_{ex} value assures a high stability against variation of load impedance. Fig. 16 shows a Rieke diagram of the GaAs FET oscillator with the BRF. The Q_{ex} value of the oscillator is about 2500. This oscillator operates over a wide load condition as shown in Fig. 16.

IV. CONCLUSION

A new type of GaAs FET oscillator with a dielectric resonator feedback circuit (DRF GaAs FET oscillator) has been proposed and fabrication procedure and performances of the oscillator have been described. The features of this oscillator are summarized as follows:

1) wide oscillation frequency range;

2) mechanical tuning with ease;

3) high-frequency stability without hysteresis;

4) superior frequency stability for ambient temperature variation;

5) low noise;

6) low-bias voltage and high efficiency.

This compact stabilized oscillator exhibited 70-mW output power with 20-percent efficiency at 11.85 GHz and a frequency stability as low as ± 150 kHz in a temperature range from -20 to $+60$ °C. The observed FM noise level of the stabilized oscillator was comparable to that of a Gunn oscillator and 0.07 $\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100-kHz off-carrier frequency.

It has been described that the oscillation performances are considerably improved by adding a band rejection filter to the oscillator.

The performances described above are excellent enough to be applied to SHF TV broadcasting systems and microwave communication systems. Besides these superior characteristics, this oscillator is very compact and simple, therefore, has wide applications for various microwave systems.

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References

[1] M. Maeda, K. Kimura, and H. Kodera, "Design and performance of *X*-band oscillators with GaAs Schottky-gate field-effect transistor," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 661–667, Aug. 1975.

[2] H. W. Tserg, H. M. Mckey, and V. Sokoloy, "Performance of GaAs M.E.S.F.E.T. oscillators in the frequency range 8-25 GHz," *Electron. Lett.*, vol. 13, pp. 85–86, Feb. 1977.

[3] P. C. Wade, "Novel F.E.T. power oscillator," *Electron. Lett.*, vol. 4, pp. 672–674, Aug. 1978.

[4] Y. Mitsui, N. Nakatani, and S. Mitsui, "Design of GaAs MESFETs oscillator using large-signal *S*-parameter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 981–984, Dec. 1977.

[5] R. J. Douvill, "A 12 GHz low-cost earth terminal for direct TV reception from broadcasting satellite," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25 pp. 1000–1008, Dec. 1977.

[6] Y. Konishi, "12-GHz-band FM receiver for satellite broadcasting," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 720–725, Oct. 1978.

[7] D. S. James, G. R. Painchad, E. Minkus, and W. J. R. Hoefer, "Stabilized 12 GHz MIC oscillators using GaAs FETs," in *Proc. 5th European Microwave Conf.*, Sept. 1975, pp. 296–300.

[8] H. Abe, Y. Takayama, A. Higashisaka, and H. Takayama, "A highly stabilized low-noise GaAs FET integrated oscillator with a dielectric resonator in the *C* band," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp.156–162, Mar. 1978.

[9] T. Saito, Y. Arai, H. Komizo, Y. Itoh, and T. Nishikawa, "A 6 GHz highly stabilized GaAs FET oscillator using a dielectric resonator," 1979 *IEEE MTT-S Dig.*, pp. 197–199.

[10] G. D. Alley and H. C. Wang, "An ultra low noise microwave synthesizer," 1979 *IEEE MTT-S Dig.*, pp. 147–149.

[11] J. K. Plourde, D. F. Linn, I. Tassuguchi, and C. B. Swan, "A dielectric resonator oscillator with 5 ppm long term frequency stability at 4 GHz," 1977 *IEEE MTT-S, Dig.*, pp. 237–276.

[12] S. Hamilton, "Microwave oscillator circuit," *Microwave J.*, pp. 63–66, Apr. 1978.

[13] R. A. Purcel, R. Bera, and D. Masse, "Experiments on integrated Gallium-Arsenide F.E.T. oscillators at *X*-band," *Electron. Lett.* vol. 11, pp. 219–220, May 1975.

[14] C. M. Krowne, "Network analysis of microwave oscillators using microstrip transmission line," *Electron. Lett.* vol. 13, pp. 116–117, Feb. 1977.

[15] T. D. Iveland, "Dielectric resonator filters for application in microwave integrated circuit," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-10, pp. 643–652, July 1971.

[16] W. R. Day, "Dielectric resonator as microstrip circuit elements," *IEEE Trans. Microwave Theory Tech.* (Correspondence), vol. MTT-18, pp. 1175–1176, Dec. 1970.

[17] J. K. Plourde, D. F. Linn, H. M. O. Bryan, and J. Thomson, "$Ba_2Ti_9O_{20}$ as a microwave dielectric resonator," *J. Amer. Ceram. Soc.*, vol. 58, pp. 418–420, Nov. 1975.

[18] T. Suzuki, A. Nara, M. Nakatani, T. Ishii, S. Mitsui, and K. Shirahata, "Highly Reliable GaAs MESFETs with a Static Mean NF_{min} of 0.89 and a standard Deviation of 0.07 dB at 4 GHz," 1979 *IEEE MTT-S Dig.*, pp. 393–395.

[19] Y. Kadowaki, M. Nakatani, T. Ishii, S. Mitsui, and K. Shirahata, "A 12 GHz 1W GaAs MESFET Amplifier," 1979 *IEEE MTT-S Dig.*, pp. 486–488.

[20] G. Satoh and S. Fujii, "MIC-BPF with dielectric resonator," IECE, Tech. Rep., MW 74-30, pp. 1–10, 1974 (in Japanese).

[21] M. Ohtoma, "Experimental evaluation of parameter in Gunn and avalanche oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 425–437, July 1972.

[22] K. Shirahata, "Stabilization of solid state microwave oscillator by loading BRF," presented at 1969 European Microwave Conf. London, England, Sept. 1969.