A Low Noise 80 GHz Silicon IMPATT Oscillator Highly Stabilized with a Transmission Cavity

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Abstract

Design consideration and experimental performance of a new transmission-cavity-controlled silicon IMPATT diode oscillator for millimeter wavelength are described. The oscillator has the frequency stability of 1×10^{-4} over temperature variation 0° - 50°C and remarkably improved noise characteristics, and is free from troublesome moding problems. Discussion is made on the circuit design that satisfies frequency stabilization, noise reduction, mode stabilization and increase of circuit efficiency.

Introduction

Millimeterwave IMPATT oscillator is an important key device for rf power sources in millimeterwave communication systems. For local oscillators in heterodyne repeaters, high degree of frequency stability, low noise and sufficient mode stability are required in addition to reasonable output power level.[1,2]

This paper describes design consideration and experimental performance of our newly developed 80GHz-band transmission-cavity-controlled silicon IMPATT oscillator that can well meet the above requirements. The oscillator has the frequency stability of 1×10^{-4} over temperature variation of 0° - 50°C with output power of more than 10dBm, and is free from troublesome mode problems. Remarkable noise reduction (in excess of at least 20dB against unstabilized oscillators) has been achieved in both C/N ratio at high modulation frequencies and near-carrier FM noise.

In the discussion, particular emphasis will be paid on the circuit design that is essential for stabilization and noise reduction.

Basic Circuit

Construction of the transmission-cavity-controlled oscillator (TCCO) is shown in Fig.1. It consists essentially of three parts:

(a) Coaxial-waveguide main cavity, in which the diode is embedded.
(b) Highly stable transmission cavity, which is coupled to the output port of the main cavity.
(c) Waveguide dummy load, which is connected to another port of the main cavity through a quarter-wavelength transformer.

The oscillator can be represented by the basic circuit shown in Fig.2-a. The transmission cavity (unloaded $Q=Q_o$) is connected to the diode port (plane 1-1') through a transmission line (admittance Y_2, length ℓ') with coupling coefficient β_1. The dummy load, which acts as a mode stabilizing resistor, is connected to the diode port in opposite direction through a transformer. Load (Y_o) is connected to output port of the transmission cavity with coupling coefficinet β_2.

The circuit in Fig.2-a can be simplified into an equivalent circuit shown in Fig.2-b. Here, the diode port is assumed to be a series connection of inductance L_e and nonlinear diode negative conductance $-G_d$ with capacitance C_j. The righthand side of plane 1-1' in Fig.2-a is replaced by parallel connection of C_o, G_o' and L_o, with a transmission line (Y_2, ℓ), while the lefthand side is expressed with gY_2. Resonant frequency ω_o, equivalent quality factor $Q_o'(\equiv\omega_o C_o/G_o')$ and coupling coefficient $\beta(\equiv Y_2/G_o')$ of the port (2-2') are given by $\omega_o=1/\sqrt{L_o C_o}$, $Q_o'=Q_o/(1+\beta_2)$ and $\beta=\beta_1/(1+\beta_2)$, respectively.

Design Consideration

In designing a local oscillator, following requirements have to be considered:

a) Low noise power at high modulation frequencies.
b) Low FM noise at low modulation frequencies.
c) High degree of frequency stability.
d) To be free from moding problems within whole tunable frequency range.
e) Small power loss due to stabilization.

It will be shown from analysis of the equivalent circuit in Fig.2-b, that all of the above requirements can be favorably satisfied in the TCCO if the following circuit conditions are adopted:

i) The diode port is series-resonant at the design frequency ω, or the series resonant frequency $\omega_s(=1/\sqrt{L_e C_j})=\omega_o$.
ii) The diode port is at the detuned open position of the transmission cavity, or $\ell=\lambda_g/4$ at design frequency ω_o.

The circuit admittance seen from the diode (3-3') has been calculated numerically as a function of ω for the above circuit conditions with various ω_o. An example of the admittance loci is shown in Fig.3. The locus has an arc of circle, which moves up and down as ω_o/ω_s increases and decreases from unity, respectively. It is obvious from Fig.3 that the slope of the susceptance (b_{in}) against frequency (ω), or $db_{in}/d\omega$, is maximum at $2Q_o'\delta=0$, where δ is given by $(\omega-\omega_o)/\omega_o$, and also for $\omega_o=\omega_s$.

If $db_{in}/d\omega$ is large, the oscillation frequency is very stable against change of diode admittance, therefore it is favorable to satisfy the requirements for FM noise reduction at low modulation frequencies and for frequency stabilization.

As seen in Fig.3, the admittance locus intersects the diode conductance line (fat line) at one point, if $\omega_0/\omega_s \neq 1$. This means that the oscillation mode is very stable, and the oscillator is free from moding problems.

The tunable frequency range in which the above situation can hold is given by

$$\omega_s - \Delta\omega_0 < \omega_0 < \omega_s + \Delta\omega_0 \qquad (1)$$

where

$$\Delta\omega_0 = \eta_{10}\omega_s / 4Q_1 g \qquad (2)$$

η_{10} is the ratio of the power going into the transmission cavity to the diode generation power for $\omega_0 = \omega_s$, and is given by

$$\eta_{10} = \beta/(g+\beta) \qquad (3)$$

Equation (1) corresponds to the condition that lefthand half of the circle in the admittance locus can intersect the diode conductance line (fat line). Since the diode negative conductance $G_d(V)$ is usually smaller than the small signal value $G_d(o)$, it is possible to avoid intersection at multi-points by increasing the circuit admittance $g_{in\infty}$ at frequencies far away from ω_0, while the circuit conductance g_{ino} for $\omega_0 = \omega_s$ should be kept at a constant value favorable for diode impedance matching (e.g., $g_{ino} Y_2 = G_d(o)/3$). Conductance g_{ino} and $g_{in\infty}$ are given by

$$g_{in\infty} = 1/(gQ_1^2) \qquad (4)$$

$$g_{ino} = 1/\{(g+\beta)Q_1^2\} \qquad (5)$$

respectively. It is obvious from Eqs.(4) and (5) that the above circuit condition is satisfied by decreasing g and increasing β, if $Q_1$is constant. This results in an decrease of the power loss in the dummy load, since the loss fraction is given by $(1 - \eta_{10}) = g/(g + \beta)$. Consequently, the overall circuit efficiency η_0, which is given by

$$\eta_0 = \eta_{10}\beta_2/(1+\beta_2) \qquad (6)$$

also increases. The minimum value of g is limitted only by the condition $(gQ_1)^2 >> 1$ for the analysis to be valid. The increase of $g_{in\infty}$ is also favorable for reduction of noise at high modulation frequencies.

Experiment

Refering to Fig.1, the temperature-stable transmission cavity is made of super invar and its resonant mode is the cylindrical TE_{013} mode. The diode is a silicon p^+nn^+ IMPATT diode prepared in our laboratory. In advance of the assembly of the oscillator, the main cavity is adjusted so that the diode port is series-resonant at the design frequency (79GHz) by selecting a proper length of the coaxial port. The adjustment is confirmed by measuring the admittance of the diode port.[3] The photograph of the TCCO is shown in Fig.4.

Fig.5 shows an example of the mechanical tuning characteristics of the TCCO. The frequency, at which the maximum output power P_o (12.5dBm) is obtained, is nearly 79GHz. Power P_d dissipated in the dummy load is 8dBm at that frequency. The mechanically tunable bandwidth, in which single mode operation is obtained, is 2GHz (78 - 80GHz).

Fig.6 shows experimental ratio (N/C) of the single sideband (1.7GHz lower than the oscillation frequency) noise to the carrier power obtained in the TCCO operated at 79.00GHz. In the figure, N/C noted as RCCO represents the value measured on a reaction-cavity-controlled oscillator[2] which uses the same main cavity and the diode. The result shows that N/C of the TCCO at f_m=1.7GHz is 20dB lower than that of the RCCO, while near-carrier AM noise is nearly the same in the both. FM noise of the TCCO is at least of 30dB lower than that of the oscillator without the transmission cavity.

The frequency shift due to temperature change is 7.5MHz/0 - 50°C (≈2ppm/°C), and that due to change of the diode current is 160kHz/mA. Other experimental performance of the TCCO is listed in Table 1.

Table 1. Experimental performance of TCCO

Frequency	79.00GHz
Output power	10dBm
DC current	205mA
DC voltage	15.2 volts
Junction temperature	200°C
Freq. stability	2×10^{-6}/°C
N/C	
DSB AM at f_m=1MHz	-100dB/3kHz BW
LSB* noise at f_m=1.7GHz	-155dB/Hz

* LSB: Lower side band.

Conclusion

A highly stabilized and low noise 80GHz-band silicon IMPATT diode oscillator that uses a high-Q transmission cavity for the stabilization has been described. The oscillator has been designed so that the frequency stabilization, noise reduction, elimination of moding problem, and increase of the circuit efficiency are all favorably satisfied. The oscillator exhibits promising capability for application in millimeterwave heterodyne repeaters.

References

1. N. D. Kenyon, "A circuit design for mm-wave IMPATT oscillators," presented at the IEEE G-MTT Int. Microwave Symp., Newport Beach, Calif., May 11-14, 1970.

2. S. Nagano and S. Ohnaka, "Highly stabilized IMPATT oscillators at millimeter wavelengths," IEEE Trans. Microwave Theory and Tech., Vol. MTT-21, PP. 491-492, July 1973.
3. _________, "Frequency stabilization of a millimeter-wave solid-state oscillator by a reaction cavity," Trans. IECE, Japan (to be published).

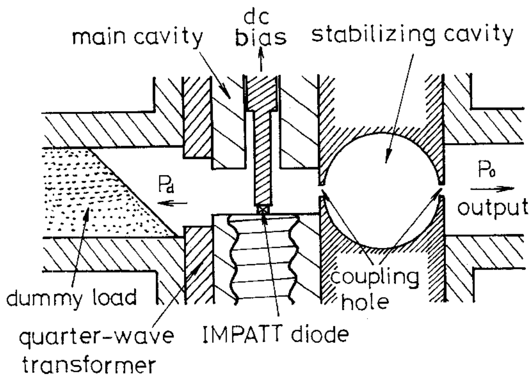

Fig.1 Cross section of TCCO

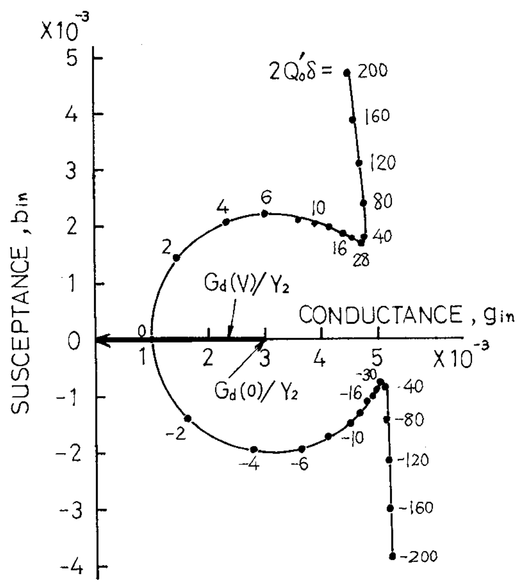

Fig.3 An example of the circuit admittance (seen from 3-3') loci. $Q_1=20$, $g=0.5$, $\beta=2$ and $\omega_0/\omega_s=1$.

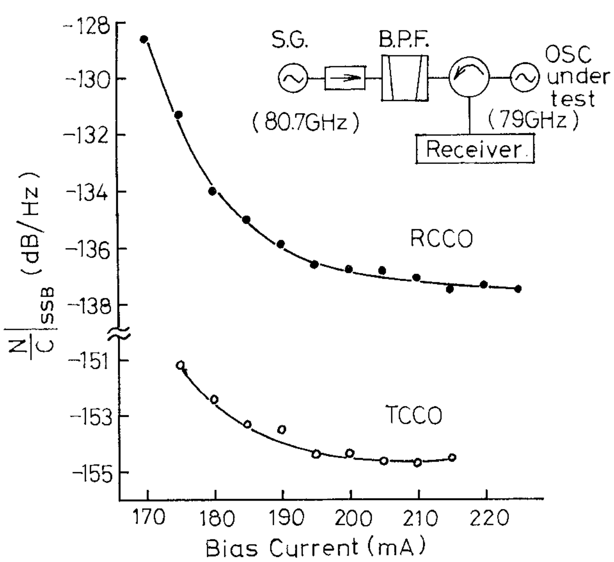

Fig.5 Mechanical tuning characteristic of TCCO.

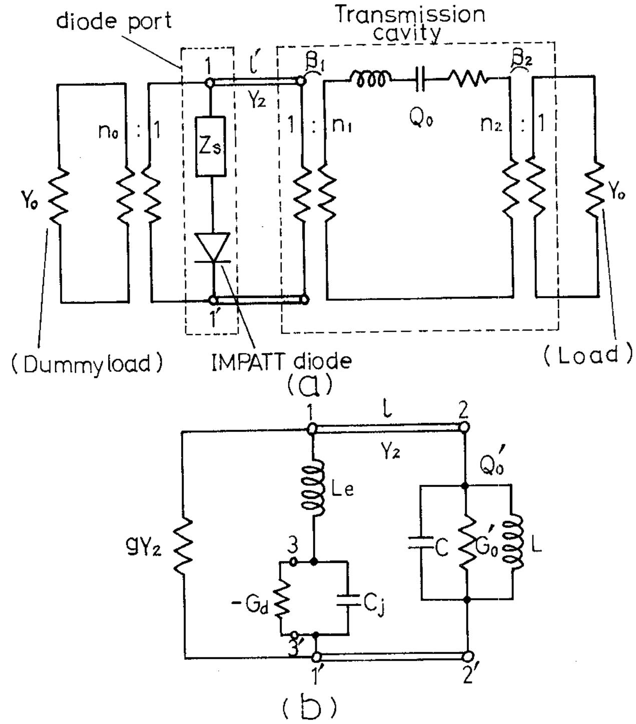

Fig.2-a Basic circuit of TCCO
Fig.2-b Simplified equivalent circuit of Fig.2-a.

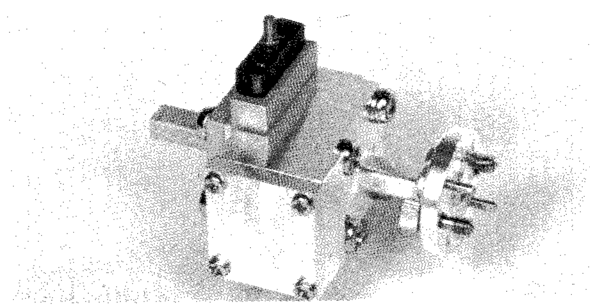

Fig.4 View of 80GHz TCCO.

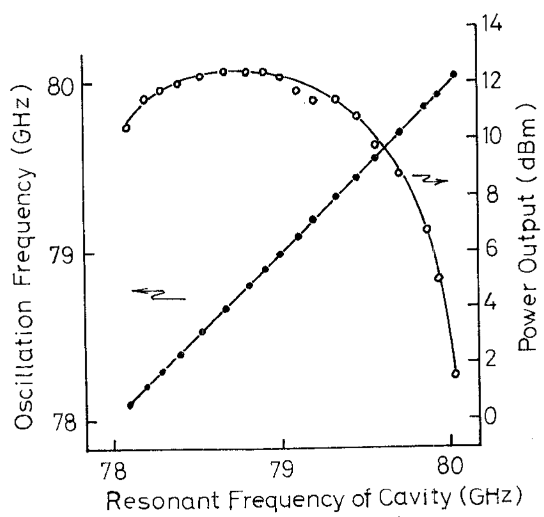

Fig.6 Experimental N/C ratio at 1.7GHz down from the oscillation frequency.

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