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Stabilization and Power Combining of Planar Microwave Oscillators with an Open Resonator

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Abstract

The fabrication advantages of planar microwave circuits over their waveguide counterparts are well known, but efforts to design highly stable oscillators and high-power oscillators in planar form with solid-state devices become increasingly difficult at the shorter microwave and millimeter wavelengths. We report herein experiments in which microstrip circuits are coupled electromagnetically to an open cavity resonator. The energy stored in the cavity leads to improved oscillator stability and lower noise sidebands. Two oscillators can be coupled to the same cavity mode, and power combining to a planar output element has been demonstrated. Although most experiments involved hybrid 10-GHz oscillators, preliminary results with a 31-GHz oscillator using a monolithic circuit indicate that the same techniques will be feasible with MMICs at millimeter wavelengths.

Introduction

High-Q resonant circuit elements improve oscillator stability with respect to load and device variations, reduce noise sidebands, and lead to higher power-combining efficiency in multiple-device oscillators. Unfortunately, resonant circuit elements in planar media such as microstrip are limited to a Q of about 300 [1]. Dielectric resonators can improve this figure, but above 30 GHz their decreasing dimensions make fabrication difficult, and the requirement for precise placement on a planar substrate runs counter to the "hands-off" philosophy of MMIC fabrication. In experiments at X and Ka bands, we have found that an open microwave resonator can support modes which couple to microstriplines. This coupling can lead to enhanced effective circuit Qs and improved oscillator noise performance. It also can be used to couple useful power to an output element which is coplanar with two oscillators. The use of an open resonator for such quasi-optical power combining, first proposed by Mink [2], has been demonstrated for what we believe to be the first time. Our discussion will begin with a brief review of open resonator modes which are pertinent to our experiments.

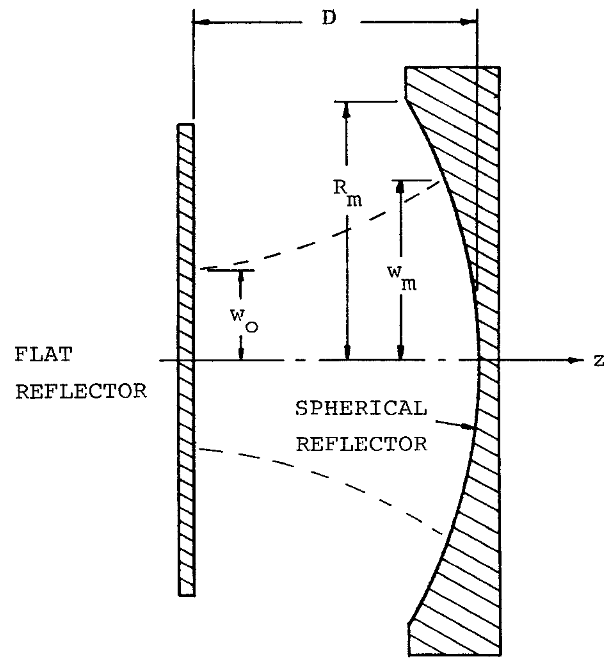

Fig. 1. Open cavity resonator showing Gaussian beam radii w_o at flat reflector and w_m at spherical reflector.

Open Resonator Modes

Consider the laser-cavity type of modified Fabry-Perot resonator shown in Fig. 1. A flat reflector is separated from a concave spherical reflector by a distance D, which is typically several wavelengths. The multiple-mode problems common to electrically large closed cavities are alleviated by the open sides, which limit the possible modes to those which are TEM to z. The modes of interest typically have a Gaussian dependence of field intensity with radial distance from the resonator axis. The radius at which the field amplitude has fallen to e^{-1} of its value on the axis is called the beam radius or scale radius. This distance at the plane reflector is given by [3]

$$w_o^2 = \frac{\lambda}{\pi}\left[D(R_o - D)\right]^{\frac{1}{2}} \qquad (1)$$

and at the surface of the spherical reflector by

$$w_m^2 = \frac{\lambda}{\pi} R_o \left[\frac{D}{R_o - D} \right]^{\frac{1}{2}} \quad (2)$$

where R_o is the spherical reflector's radius of curvature and λ is the wavelength in the medium. For a constant wavelength and R_o, increasing the cavity length D narrows the beam slightly at the plane reflector and widens it at the spherical reflector, as Fig. 2 shows.

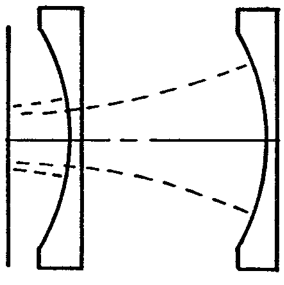

Fig. 2. Effect of cavity length upon beam sizes at reflectors: (a) short cavity (b) long cavity.

The Q of an empty resonator whose beam radii lie well within the physical boundaries of the reflectors can be estimated by the approximate expression $Q = D/2S$ [3], where S is the skin depth in the reflector material. Measured Q's exceeding 10^5 have been achieved with resonators of reasonable dimensions at 35 GHz [3], although the introduction of objects within the cavity's fields will lower the Q because of scattering and dissipative losses.

The resonant frequency of the $\mathrm{TEM}_{p\ell q}$ mode of the empty resonator is given by [3]

$$f = \frac{c}{2D} \left\{ q + 1 + \frac{(2p + \ell + 1)}{\pi} \tan^{-1} \left[\left(\frac{D}{R_o - D} \right)^{\frac{1}{2}} \right] \right\} \quad (3)$$

The indices p and ℓ relate to the number of radial and azimuthal field reversals, respectively. The index q determines the number of half guide wavelengths along the resonator axis.

Open Resonator Coupling to Microstrip Line

Since the fields near the axis of an open resonator are relatively intense, planar circuit elements not usually considered to be radiators show significant coupling to open resonator modes. Fig. 3 illustrates an experiment in which a 50–ohm microstrip line was coupled to modes set up between the microstrip ground plane and a spherical reflector facing it. The transmission loss measurement of the line's $|S_{21}|$ in Fig. 4 revealed the mode resonances as dips near the theoretically calculated frequencies indicated. Capacitive loading of the cavity by the substrate accounted for the slight disparity between calculated and measured values. This experiment confirmed that high–Q modes could exist in the presence of circuit elements within a high–field region.

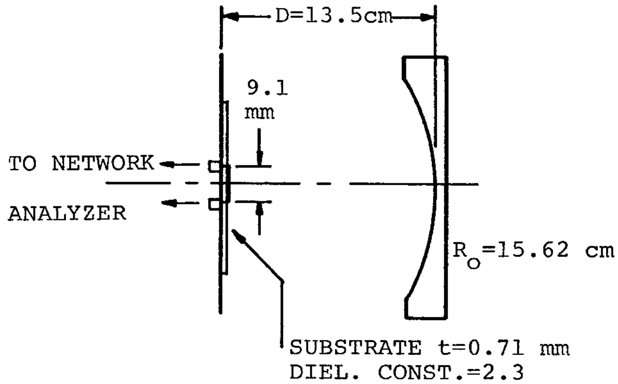

Fig. 3. Open resonator coupling to microstrip line.

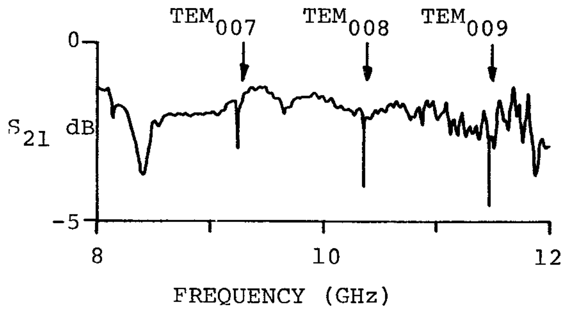

Fig. 4. Transmission loss $|S_{21}|$ versus frequency for microstrip line of Fig. 3 coupled to TEM_{00q} modes of open resonator.

Planar Gunn–Diode Oscillators

Next, an X–band microstrip oscillator using a M/A-COM MA–49508 Gunn diode was designed around a 27–ohm line that was approximately a quarter–wave long at 10 GHz. The diode was soldered to the low–impedance end of the line, while the high–impedance end was coupled through fringing fields to a surface–launch RF output connector through a set of six fingers, as shown in Fig. 5. Various fingers could be connected either to the quarter–wave resonator or to the output, allowing repeatable and stable adjustment of tuning and output coupling.

Up to 2 or 3 mW could be obtained by means of this coupling method before oscillations ceased due to overloading. While the diodes used were rated for a minimum output power of 10 mW in a properly designed waveguide cavity, the higher losses associated with microstrip circuitry made it difficult to achieve this figure, although further improvements could no doubt be made.

Stabilization with Open Resonator

The output spectrum of the free–running Gunn–diode oscillator by itself is shown in Fig. 6(a). In addition to some instability of the carrier frequency due to imperfect power supply filtering, there are relatively high noise sidebands extending out to at least 5 MHz either side of the carrier.

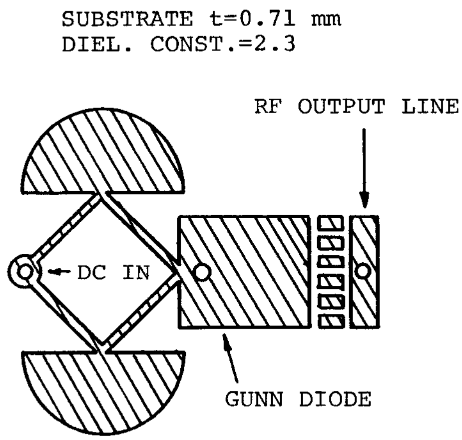

Fig. 5. Planar Gunn–diode oscillator layout.

Kurokawa [4] has shown that the mean-square phase fluctuations of a free-running oscillator go as $(\omega Q_{ext})^{-2}$, where ω is the frequency deviation from the carrier and external Q is most generally defined as

$$Q_{ext} = \frac{2\pi(\text{Energy stored})}{(\text{Energy delivered to load per cycle})} \quad (4)$$

Clearly, for a given power output, increased energy storage in the oscillator circuit will improve phase noise sidebands.

When the planar oscillator of Fig. 5 was coupled to the open resonator by placing the spherical reflector at a distance $D = 11.6$ cm above the flat oscillator ground plane, the greatly improved spectrum of Fig. 6(b) resulted. Output power decreased only about 1 dB, and subsequent experiments have shown that similar noise improvements can be obtained with no output power reduction. Although these qualitative results must be explored more thoroughly before conclusive statements can be made, this experiment shows unequivocally that coupling to an open resonator mode can improve the noise performance of a planar oscillator, with little or no accompanying output power penalty.

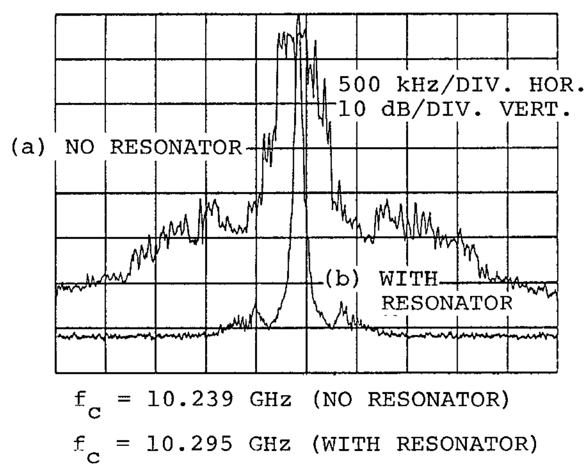

Fig. 6. Output spectra of planar oscillator: (a) No open resonator; $P_{out} = 2.1$ mW (b) With open resonator; $P_{out} = 1.7$ mW.

Power Combining of Two Oscillators

Power combining of the output of two planar oscillators was demonstrated with the configuration illustrated in Fig. 7, which is a view looking down on the circuits from the spherical reflector. The distance separating the oscillators was chosen so that the quarter-wave resonators would fall inside the beam radius shown. A modified microstrip patch antenna was mounted between the oscillators over a slot cut in the ground plane. Through this slot, an adjustable capacitive probe feed coupled to the patch antenna through its dielectric substrate. Adjustment of the output probe position along the slot beneath the patch allowed impedance matching to be achieved for a wide variety of modal fields.

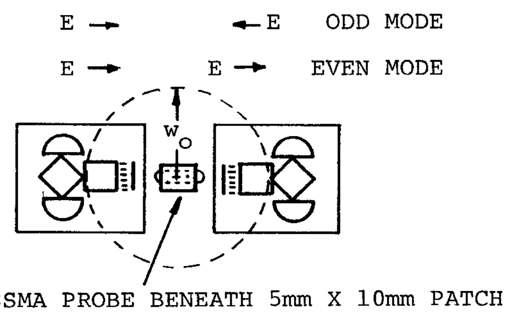

Fig. 7. Power combining experiment using two planar oscillators and output patch antenna.

In operation, the DC bias of the two oscillators was adjusted to obtain nearly equal free-running frequencies in the absence of the open resonator. Although coupling between the two oscillators without the spherical reflector was quite small, it was still sufficient to cause them to injection-lock to each other in one of two modes, which we term the odd mode and the even mode. The existence of these modes was verified by phase measurements of the oscillators' coaxial connector outputs. Modes of inter-injection-locked oscillators are currently under study and have been addressed elsewhere [5,6]. These same modes are found when the open resonator is formed by placing the spherical reflector above the oscillators' ground plane. The odd oscillator mode couples to the TEM_{01q} resonator modes, while the even oscillator mode couples to the TEM_{00q} modes.

As the spherical mirror was moved closer to the running oscillators, various resonator modes were excited by the oscillators and "took over" the oscillator frequency in turn. Adjustment of the reflector position and output probe coupling led to output power of several milliwatts from the central patch antenna where only a few microwatts was available before the open resonator was formed. Maximum output power of 13.3 mW was obtained from the central patch antenna, with the relatively small reflector-ground plane spacing $D = 29$ mm. The TEM_{011} open resonator mode was evidently responsible for this relatively efficient transfer of power from the two oscillators to the central patch. Although quantitative evaluation of power combining efficiency must await more detailed experiments, 13.3 mW far exceeds the 4–6 mW that could be obtained by combining the coaxial outputs of the oscillators, and approaches the 20 mW minimum to be expected from a closed waveguide cavity power combiner using two 10 mW diodes. The significance of this experiment lies in the planar nature of the circuitry. Other than the spherical reflector itself, all components including the active devices can in principle be integrated monolithically.

Ka–Band Oscillator Experiment

A 31–GHz Gunn–diode oscillator incorporating a monolithic *GaAs* microstrip resonator was studied as a possible candidate for stabilization by means of an open resonator. The oscillator housing was not designed to be a millimeter–wave plane reflector, and it afforded only about 5 cm^2 of usable reflector area near the oscillator circuit. Because of this, scattering of the resonator mode energy lowered the Q substantially, and no measurable improvement in the performance of the oscillator has yet been observed. However, we were able to measure the influence of the TEM_{00q} modes on the oscillator's output frequency by placing the oscillator in a configuration similar to Fig. 3 and varying the resonator length D with a motorized translation stage. Fig. 8 shows the oscillator's frequency shift from its free–running frequency f_o as a function of resonator length, together with theoretical cavity lengths corresponding to the various modes having a resonant frequency of f_o. The modes are seen to correspond to distances at which the oscillator frequency shows sharp peaks. These results indicate that the relatively weak radiation from a *GaAs* microstrip circuit is sufficient to interact measurably with open–resonator modes. Changes in the oscillator ground plane to make it a more efficient reflector of millimeter waves should lead to higher mode Qs and more useful oscillator–resonator interactions.

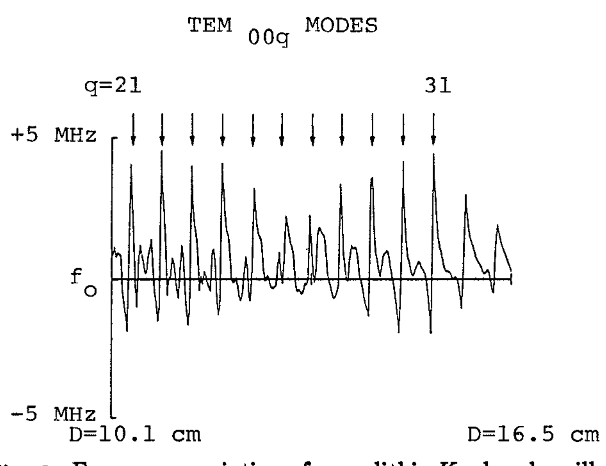

Fig. 8. Frequency variation of monolithic *Ka*–band oscillator with resonator length D in open resonator configuration of Fig. 3.

Conclusions

We have demonstrated that the open–cavity resonator formed in the space between a spherical reflector and a flat circuit substrate and ground plane can sustain modes that couple usefully to microstrip circuits. Oscillator stabilization and power combining of two oscillators have been demonstrated successfully at X–band, and preliminary experiments indicate that similar techniques will be useful above 30 GHz. In principle, all components of these circuits except for the spherical reflector can be fabricated by monolithic integrated circuit methods. The prospect of multiple–device oscillators using slightly modified housings to sustain open–resonator modes may lead to greatly improved stability and power combining efficiency for MMICs. The open resonator is basically a quasi–optical device whose performance improves at shorter wavelengths. While its dimensions are somewhat large for practical applications below 30 GHz, millimeter–wave resonators can be made in sizes that are quite compatible with conventional circuit housings. Thus, the techniques outlined in this paper can contribute to MIC designs at frequencies where conventional methods begin to falter.

Acknowledgements

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