Millimeter-Wave Power Combiner Using Quasi-Optical Techniques

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Abstract—**A millimeter- or submillimeter-wave combiner using a quasi-optical open resonator to effectively combine the power output of several solid-state oscillators to a single-frequency is described. The combiner makes use of a symmetrical concave spherical resonator with dielectric wedge launchers as energy couplers. To demonstrate feasibility of this concept, experiments were carried out by using two InP Gunn oscillators at 60 GHz, and a combining efficiency of 54 percent has been achieved.**

I. Introduction

IN THE PAST, MANY power-combining approaches using circuit techniques have been investigated in order to increase the power output capabilities of solid-state devices. Microwave power-combining techniques fall mainly into three categories: nonresonant hybrid combiners, nonresonant N-way combiners, and resonant N-way combiners. With hybrid or serial combiners, the outputs of several discrete oscillators are successfully combined [1]–[5]. In a nonresonant N-way combiner, the output from all devices is combined in one step, similar to Wilkinson-type combiners [6]–[8]. Kurokawa and Magalhaes [9] were first to use rectangular resonant cavity combiners. Harp and Stover [10] later used a cylindrical resonant cavity and similar techniques were used in subsequent investigations [11]–[13]. An extensive review of microwave power-combining techniques was given by Russell [14]. The combining method used in this paper should be classified as N-way resonant cavity structure.

Power combining at millimeter frequencies has evolved from an extension of techniques developed at microwave frequencies by frequency scaling. The most commonly used combining technique at millimeter-wave frequencies is the resonant N-way combiner, where one resonant cavity combines N discrete oscillators. Both Gunn devices and IMPATT devices have been combined in this way [15]–[17].

However, these conventional resonant waveguide combiners are seriously limited in power output and combining efficiency in the millimeter-wave region. This limitation is a direct consequence of the serious size and volume restrictions of waveguide resonators and circuit combiners necessary to achieve acceptable mode separation and avoid multimoding. This follows from the fact that in a closed-cavity resonator, the number of possible resonant modes within a given frequency interval is directly proportional to the volume of the resonator and the square of the frequency. Consequently, as frequency increases into the millimeter- and submillimeter-wave range, the mode density of the closed resonator increases, mode separation decreases, and excitation of single-frequency oscillation becomes increasingly more difficult.

Since Gunn devices and IMPATT devices have a negative resistance over a wide frequency range, a low-mode density, small-volume waveguide resonator is required to limit multimoding. This size limitation of the waveguide resonator imposes a strict limitation on the number of solid-state devices that can be combined. Moreover, as the millimeter operating frequency increases to 100 GHz and beyond, the geometrical constraints of conventional waveguide combiners are severely compounded due to fabrication difficulties.

This paper presents a new approach to power combining of solid-state devices in the millimeter- and submillimeter-wave frequency region. It is based on a quasi-optical open resonator similar to laser resonators where dimensions are large compared to the wavelength and which offers an attractive approach to overcome the above limitations. Its usefulness is derived from the characteristic that most of its higher order modes are eliminated on the sides. Details of such an approach will be presented in this paper.

II. Resonator Description

In its essential form, the quasi-optical resonator for power combining consists of two highly polished reflectors with suitable radiation launchers facing each other at a certain distance which is large compared to the wavelength. Electromagnetic radiation launched into the resonator from an array of diode oscillators bounces back and forth between the reflectors establishing a standing-wave pattern along the resonator axis. The mode pattern is affected by both the longitudinal spacing and the curvature of the reflectors. Signal interaction occurs between the resonant modes and the individual oscillators.

The basic properties of the quasi-optical resonator can be derived from optical resonators which have long been used in the laser field. An extensive review was given by Kogelnik [18].

For our design purposes, only stable resonators will be considered which are characterized by the stability criterion

$$0 \leqslant g_1 g_2 \leqslant 1 \tag{1}$$

Manuscript received May 21, 1982; revised August 27, 1982.

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where the g parameters are defined as

$$g_1 = 1 - \frac{d}{R_1} \quad \text{and} \quad g_2 = 1 - \frac{d}{R_2} \tag{2}$$

where d is the reflector spacing and R_1, R_2 are the radii of curvature of the reflectors. In addition, for simplicity only, symmetrical resonators with circular reflectors are considered for which

$$R_1 = R_2 = R \quad \text{and} \quad g_1 = g_2. \tag{3}$$

Under these conditions, possible resonator arrangements range from the plane-parallel system ($R = \infty$; $g_1 = g_2 = 1$), the focal system ($d = R/2$; $g_1 = g_2 = 1/2$), the confocal system ($d = R$; $g_1 = g_2 = 0$), to the concentric system ($d = 2R$; $g_1 = g_2 = -1$).

A plane-parallel reflector arrangement, while suitable, is not an ideal resonator, due to the high degree of reflector flatness required to keep diffraction losses low for high Q and the critical alignment for reflector parallelism. Perturbations due to launchers make plane-parallel reflector alignment practically impossible.

A dramatic decrease of diffraction losses results from the use of spherical reflectors. A quasi-optical resonator as shown in Fig. 1 offers the best approach for power combining of millimeter-wave sources. It consists of concave spherical reflectors of equal curvature separated by a distance between 1–2 times their common focal length. The reflectors are circular with uniform high reflectivity over the reflecting surface. Input coupling is accomplished through dielectric launchers (antennas) located somewhat off-center in the input reflector. Output coupling is achieved through a dielectric launcher located at the center of the output reflector. Its mode of operation was described before. The modes of this resonator are transverse electromagnetic (TEM_{mnq}) waves with negligible longitudinal field components. The transverse field distribution of low-order resonant modes is closely confined around the axis of the resonator. The mode characteristics are governed by the reflector curvatures and the reflector spacing, provided the reflector apertures are sufficiently large to intercept the bulk of the incident beam. The resonant-mode frequencies or the mode spectrum in a stable open resonator is governed by the standing-wave equation which follows from the requirement that the phase shift of a round-trip of a resonant-mode wave be a multiple of 2π. This leads to the following expression:

$$f_{mnq} = \left[q + (m+n+1) \frac{\cos^{-1} \pm \sqrt{g_1 g_2}}{\pi} \right] \frac{c}{2d} \tag{4}$$

with m, n as the transverse mode numbers, q as the axial mode number, and c as the velocity of light. The mode number q measures the number of half-wavelengths of the standing-wave pattern along the resonator axis. The axial mode separation or the frequency separation between two modes with the same transverse mode numbers and adjacent axial mode numbers is simply $f_{mnq+1} - f_{mnq} = \Delta f = c/2d$. Each axial mode is split into a set of transverse mode resonance frequencies where spacing (density) depends on the specific resonator type. For a confocal resonator, the symmetric ($m + n =$ even) transverse modes coincide with axial modes and the nonsymmetric ($m + n =$ odd) ones lie halfway between axial modes.

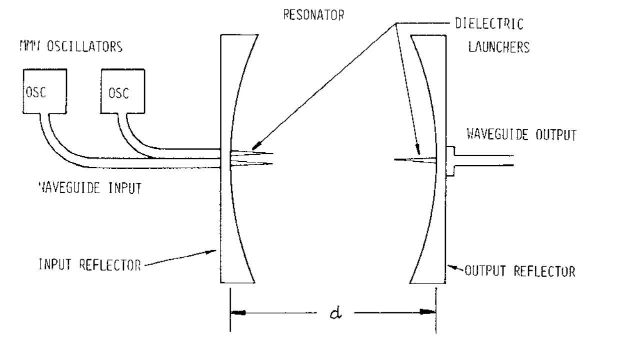


Fig. 1. Quasi-optical millimeter-wave power combiner schematic.

The fundamental or lowest order mode ($m = n = 0, TEM_{00q}$) is of Gaussian shape and represents the mode with the lowest loss. This follows from the fact that higher order modes have a field distribution extending farther from the resonator axis. Consequently, their energy is less concentrated near the resonator axis and a larger fraction is lost due to diffraction at the mirror edges.

The beam contour is defined by hyperbolic curves and the beam radius or spot size is taken as the contour of the beam where the field amplitude has decreased to e^{-1} of its axial value. Beyond this boundary, the field and, consequently, the energy of the beam die off very rapidly. The phase fronts of the propagating beam are nearly spherical and represent suitable positions for spherical reflectors to form the open resonator. For a symmetric resonator with identical reflector curvatures, the minimum beam size occurs in the center of the resonator and the beam radii at the center w_0, and at the reflectors w_1, w_2 are given by the following equations:

$$w_0 = \left(\frac{d\lambda}{2\pi} \right)^{1/2} \left(\frac{1+g}{1-g} \right)^{1/4} \tag{5}$$

and

$$w_1 = w_2 = \left(\frac{d\lambda}{\pi} \right)^{1/2} \left(\frac{1}{1-g^2} \right)^{1/4}. \tag{6}$$

Feedback coupling or signal interaction occurs between the resonant mode and the individual oscillators leading to injection locking and single-frequency operation.

Output coupling is provided by a dielectric launcher (antenna) to transfer power from the resonator mode to the output waveguide at the center of the end reflector. With the energy maximum of the Gaussian beam occurring at the resonator axis, this will provide the condition for strong output coupling. Therefore, the quasi-optical or open resonator combines the necessary features for effective combiner operation in the millimeter-wave region.

There are no critical geometrical design parameters for the spherical quasi-optical resonator. Its size is large compared to the wavelength of operation. Reflector parallelism is not a strict requirement and resonator alignment is a relatively easy task. The reflector diameter must be large enough to capture the bulk of the input radiation and contain the energy of the low-loss, low-order modes well within the reflector aperture.

A good approximation for the Q of the resonator is given by

$$Q = \frac{2\pi d}{\alpha\lambda} \tag{7}$$

with α as the fractional power loss per reflection consisting of reflection and diffraction losses. Reflection losses of well-polished reflectors for millimeter wavelengths should be negligible. Diffraction losses for low-order modes are small provided the Fresnel number

$$N = \frac{r_1 r_2}{\lambda d} \tag{8}$$

is much larger than unity, where r_1, r_2 are the radii of the reflectors, d is their separation, and λ is the wavelength. Consequently, the Q value is high for the open resonator.

Parabolic reflectors can also be used for the open resonator. However, their advantages are negligible since, for the reflector dimensions involved, they closely approximate spherical surfaces.

Low-loss dielectric wedge launchers with an overall length of approximately 5λ can be used for input and output coupling.

III. Combiner Design

To demonstrate the feasibility and characteristics of quasi-optical resonator configurations for the development of millimeter-wave power combiners for solid-state oscillators, a quasi-optical combiner at 60 GHz using two InP Gunn oscillators was designed following the principles as discussed before. Fig. 2 shows a photograph of the actual combiner.

A. Resonator

The resonator is formed by two symmetrical concave spherical reflectors made of highly polished aluminum with a diameter of 15 cm, a radius of curvature of 30 cm, a focal length of 15 cm, and a reflector spacing of 15 cm. In this resonator, the focus of the exit reflector was on the input reflector and vice versa. The output of the oscillators were coupled into the resonator via two WR-15 waveguide apertures arranged vertically near the center of the input reflector and the output coupling was made via a WR-15 waveguide aperture located at the center of the end reflector. The coupling apertures were fabricated by electrostatic discharge machining. The input apertures were located either closely spaced in the center of the input reflector or separated vertically by 19 mm without changing the performance of the combiner noticeably.

The spot size or minimum beam radius of the Gaussian mode at the center of the resonator is 1.44 cm and broadens by diffraction to 1.66 cm as it reaches the reflector surfaces, but remains well within the reflector surface.

For our typical resonator arrangement with $d = 15$ cm, the longitudinal mode separation $\Delta f = 1$ GHz, as measured with the spectrum analyzer, agrees with the calculated value.

The Fresnel number N is equal to 7.5.

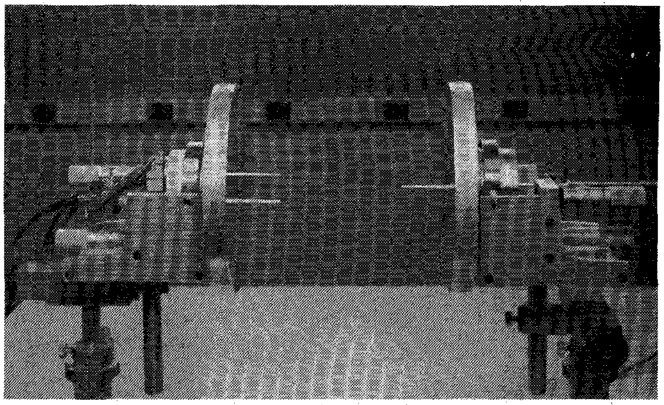


Fig. 2. Dual oscillator quasi-optical power combiner at 60 GHz.

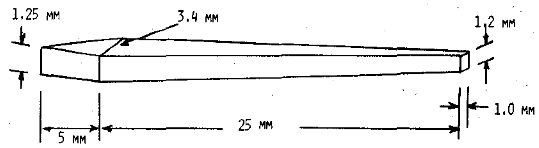


Fig. 3. Tapered dielectric launcher (polyethylene).

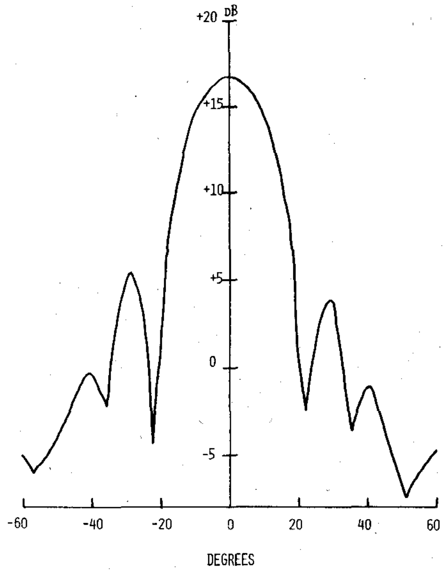
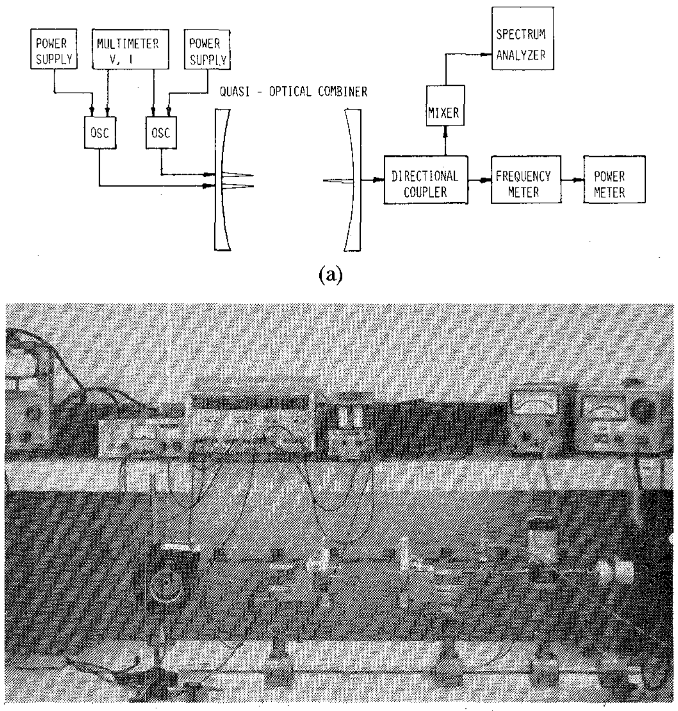


Fig. 4. Typical radiation pattern of dielectric launcher (gain 16.8 dB, beamwidth 23° H-plane.)

B. Launchers

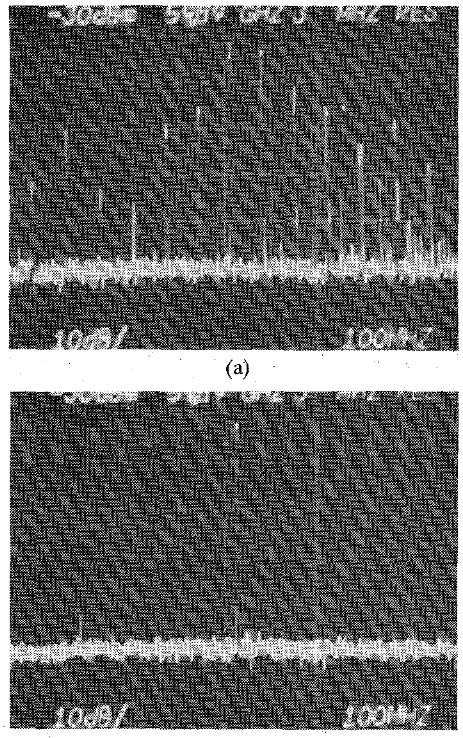
Low-loss tapered dielectric rod launchers of rectangular cross section matched into the waveguide apertures were used for input coupling to assure that most of the energy is incident on the opposite reflector. A similar launcher was used at the output end. The waveguide–dielectric launcher transitions were properly matched for optimum power transfer. The launchers, as shown in Fig. 3, are made of polyethylene with a relative permittivity of 2.25 and a loss tangent of 0.0002. The launchers with a typical length of 5λ had a gain of 16.8 dB and a half-power beamwidth of 23° in the H-plane. A typical H-plane radiation pattern of the launchers used is shown in Fig. 4. Since the E-plane radiation pattern is very similar it has been omitted. Dielectric tapered rod launchers or antennas have been fairly



(a)

(b)

Fig. 5. Measurement system for quasi-optical millimeter-wave power combiner. (a) Schematic. (b) Photograph.



(a)

(b)

Fig. 6. Mode spectrum of quasi-optical power combiner at 60 GHz. (a) Nonresonant, noncombining. (b) Resonant, combining, single frequency.

thoroughly investigated analytically and experimentally [19]–[21].

C. Oscillators

Two InP Gunn-diode oscillators with similar frequency (60.07 GHz and 60.03 GHz) and similar output power (30.5 mW and 29.5 mW) were used in this investigation. The Gunn diodes are mounted in an N-34 package, operated in a coaxial-waveguide circuit and bias tuned for frequency adjustment. No isolator was used to permit feedback coupling with the quasi-optical resonator mode.

D. Experimental Setup

The combiner assembly was mounted on an optical bench. The carriers holding the reflectors provided longitudinal, transverse, and vertical motion of the reflectors as well as tilt and rotation about their vertical and horizontal axis, some with micrometer precision. The arrangement is shown in Fig. 5. A Tektronix 7L18 spectrum analyzer with a Hughes external mixer was used to observe the spectral purity of the signal.

IV. Experimental Results

The signal exiting from the end reflector was coupled through a 10-dB coupler into a Tektronix 7L18 spectrum analyzer with a Hughes external mixer to determine spectral purity. The remaining 90 percent of the output power was coupled to a Hitachi frequency meter and into an Anritsu power meter for frequency and power measurements. After micrometer adjustment of the reflectors to achieve resonance, a combining efficiency of 54 percent was obtained from the two InP Gunn oscillators at 60.07 GHz. The spectrum analyzer clearly showed the merging of the two signals into one as resonance occurred, as shown in Fig. 6. Because the Q of the open resonator is very high, especially when compared to the Q of a Gunn-diode cavity, we found that after resonance was achieved the combiner yielded a signal with very small FM noise.

Under resonance conditions, reflections at the input reflector are negligible. Phase matching elements such as phase shifters and $E-H$ tuners had no significant effect on the overall performance of the combiner. We have observed a definite beam narrowing along the resonator axis under resonance conditions. The mode diameter is smallest at the center of the resonator and increases towards the reflector surfaces in line with theoretical considerations of the resonant-mode structure. However, we also found a noticeable diffraction at the reflector edges and spill over of electromagnetic energy at the sides of the resonator.

Dielectric launchers also contribute to the losses, more as a perturbing medium rather than dielectric losses.

Losses due to power reflected back to the diodes were minimized by adjusting longitudinal positions of the dielectric launchers to make the waveguide path to the diodes a multiple of half wavelength.

V. Summary and Conclusions

Effective power combining at millimeter-wave frequencies has been achieved by a quasi-optical open resonator. The resonator consisted of a spherical reflectors–dielectric launcher arrangement. A combining efficiency of 54 percent was achieved at 60 GHz with a dual InP Gunn oscillator array. With optimum impedance matching and coupling between input, resonator, and output, and effective excitation of fundamental Gaussian mode requiring an extensive theoretical analysis, combining efficiency should increase significantly.

This concept can be extended to combine the power output of many solid-state millimeter-wave oscillators. Only two oscillators were combined in the experiments reported in this paper because of the limited supply of suitable Gunn oscillators.

As frequency is increased to 150 GHz and beyond, all previous millimeter-wave combiners employing conventional waveguide resonators become increasingly difficult, less efficient, and the number of diodes to be combined decreases rapidly. In contrast, the quasi-optical combiner concept should work equally well with no physical constraints or reduction in the number of oscillators to be combined. Therefore, this quasi-optical combiner should have practical applications more in submillimeter frequencies and large arrays of diodes than at low millimeter-wave frequencies with few diodes where conventional waveguide combiners work well.

Acknowledgment

The authors are indebted to T. Ewanizky for his assistance in the early part of this investigation, to Dr. F. Schwering for his helpful discussions, and to Dr. H. Jacobs for his continuous encouragement.

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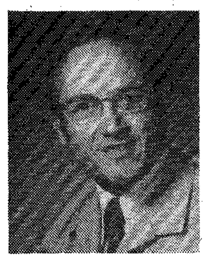

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