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Design of a millimeter wave quasi-optical power combiner for IMPATT diodes

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Abstract

A quasi-optical power combiner was designed to couple millimeter wave radiation from a number of IMPATT diodes to produce a single power source. Phase coupling at 35 GHz has been accomplished and rf power exceeded the sum of the individual diode outputs. Millimeter waves of high spectral purity, less than 50 kHz bandwidth, were produced. Although problems of coupling loop impedance matching have not been fully solved, the results of this experiment should encourage the production of large arrays of millimeter wave diodes in monolithic integrated circuits.

Introduction

Conventional waveguide power combiners are limited in power output, efficiency, and number of sources that may be combined in the millimeter wave region. This limitation is a consequence of the requirement that linear dimensions of conventional waveguide resonators be of the order of one wavelength to achieve acceptable mode separation and to avoid multimode operation. On the other hand, quasi-optical resonators have linear dimensions large compared to wavelength and they offer an attractive approach to overcome these limitations. In addition, the Q of such resonators is high, resulting in a pure output frequency spectrum from a quasi-optical millimeter wave power combiner. An experimental investigation of quasi-optical millimeter wave power combiners based upon the theory developed earlier by Mink[1] is discussed in this paper. The approach utilizes an array of source elements placed at the surface of one reflecting surface on an open resonator. For testing purposes, energy is extracted at the other reflector through a conventional waveguide.

Combiner configuration

To experimentally investigate the feasibility of quasi-optical power combining of millimeter wave sources, an approach which combines a wavebeam or Fabry-Perot resonator is used as the combining element and IMPATT (Impact Avalanche Transit Time) diode sources are configured in a rectangular array with each diode connected to a loop coupling element. The cavity configuration is shown in Fig. 1. For ease of fabrication, a wavebeam resonator of circular symmetry is employed in this experiment. The resonator consists of two reflecting surfaces which are large relative to the operating wavelength. One surface is a planar reflector and the other is curved such that it tends to "focus" the electromagnetic energy at the planar reflector.

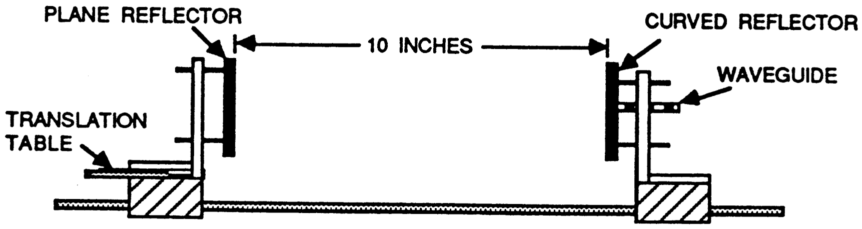

Figure 1. Quasi-optical cavity.

A goal of this experiment was to show that a large number of sources could be combined and that the IMPATT diode sources would cohere with each other in the combiner environment. Also, for this experiment, it was decided to utilize commercially available IMPATT sources (Hughes 60 GHz CW IMPATT). Because such devices are already mounted and since one side of the diode is connected to a heat sink, one could not easily employ the coupling technique of balanced electrical dipoles as discused by Mink[1]. To achieve efficient coupling with a dense array of elements it was decided that loop coupling could be utilized. Other techniques could have been employed however, but they are not easily extrapolated to a large number of sources. Space limitations here prevent the presentation of the theory of loop coupling which will be published at a later date. Each source is attached to a small radiating loop as shown in Fig. 2. The diode heat sink is embedded in a copper rod 1 mm greater in diameter. A filter network is then milled in the copper as well as a slot to permit passage of the loop wire to the diode cap. This assemblage is then embedded in the plane surface of the reflector and biasing currents are passed through the filter network and the loop to the diode. The filter network consists of a series of quarter wavelength transmission lines designed to present a low impedance at the point where the loop passes through the ground plane.

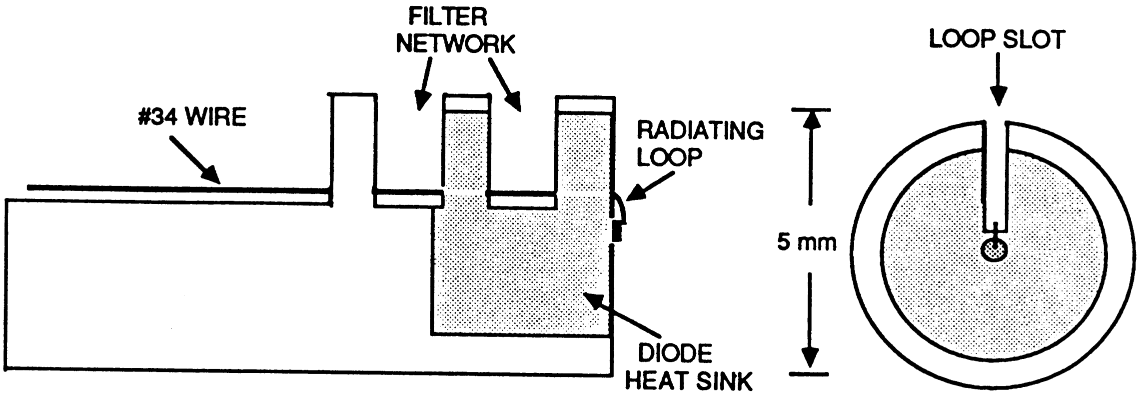

Figure 2. Diode package and rod assembly, side and front view.

Resonator design

Quasi-optical resonators are based upon reiterative wave beams or beam modes. These modes were first described by Goubau and Schwering[2] and for the purposes of this experiment only the lowest order mode is of interest. In the transverse direction the lowest order mode may be expressed by a Gaussian distribution. In directions transverse to the direction of propagation, characteristic dimensions of the fields within the wavebeam resonator are much larger than those of a conventional waveguide. They range from about 10 to 100 wavelengths.

Modes of rectangular symmetry are utilized for this investigation since the beam mode as well as source coordinates of a regular rectangular array may be expressed in Cartesian coordinates. The mode function utilized is expressed below:

$$\left|E_{00}^{\pm}(x,y,z)\right| = \frac{(\mu/\varepsilon)^{1/4}}{\sqrt{\pi\bar{X}\bar{Y}}}(1+u^2)^{-1/4}(1+\upsilon^2)^{-1/4}\exp\left\{-\frac{1}{2}\left[(x/x_z)^2+(y/y_z)^2\right]\right\} \tag{1}$$

where

$$u = z/k\bar{X}^2 \quad , \quad \upsilon = z/k\bar{Y}^2$$

$$x_z = \bar{X}^2\left(1+\frac{z^2}{k^2\bar{X}^4}\right) , \quad y_z = \bar{Y}^2\left(1+\frac{z^2}{k^2\bar{Y}^4}\right)$$

and the relationship between the field components is

$$E^{\pm}_{x00} = \pm\sqrt{\frac{\mu}{\varepsilon}}\, H^{\pm}_{y00} \quad , \quad E^{\pm}_{y00} = \mp\sqrt{\frac{\mu}{\varepsilon}}\, H^{\pm}_{x00} \tag{2}$$

The $E^{\pm}$ field represents the desired wavebeam mode and the + sign refers to traveling waves propagating in the positive z direction, and the - sign refers to waves propagating in the negative z direction. The quantities $\bar{X}$ and $\bar{Y}$, which determine the decay of the field in the x and y directions, are called the mode parameters. Mode parameters are adjusted so the wavebeam satisfies an imposed boundary condition. When one considers a resonant structure, the condition which must be satisfied is that, for each round trip of a wave within the resonator, the field repeats itself in both amplitude and phase distribution. It has been shown that the mode parameters are functions of the resonator configuration and wavelength. For the resonator described above the mode parameter is[3]

$$k\bar{X} = k\bar{Y} = \sqrt{(2-D/F)FD} \tag{3}$$

where

$k = 2\pi/\lambda$

D = distance between the reflecting surfaces

F = focal length of the curved surface

IMPATT diodes

As previously mentioned, Hughes 60 GHz CW IMPATT diodes were used to test the theory of quasi-optical power combining. Diodes selected were silicon double drift devices with a doping profile of p^+pnn^+, where the p^+ and n^+ regions allow for ohmic contacts to be made to the external circuit. As commercially packaged, the p^+ region is bonded to metalized diamond which is thermally and electrically conductive. The diamond is then embedded in a 0.3 x 0.4 cm cylindrical copper encasement to serve as a heat sink and mount. The n^+ region is coupled to a gold band and then to a gold button 0.09 cm in diameter sealed to a quartz ring standoff 0.01 cm above the active device as shown in Fig. 3. These packaging dimensions are believed to be critical to the experimental results discussed later. The IMPATT diodes are designed to operate at 250°C with a MTBF of 10,000 hours. At the rated bias current, approximately 7 watts of heat would be dissipated from each diode. The diodes used were certified individually by the manufacturer with the following intrinsic variations: capacitance ~ 1.50 to 1.91 pf; breakdown voltage (minimum voltage for current to flow) ~ 22.4 to 24.6 volts; bias voltage for rated CW freqency ~ 26.2 to 29.3 volts; rf power ~ 210 to 280 mW; rated freqency ~ 59.0 to 61.6 GHz. Differences in doping concentrations, device thickness, and operating temperature (which induces thermal expansion in the p and n regions) affect the transit time of the electrons and hence the rf frequency for a particular diode.[4]

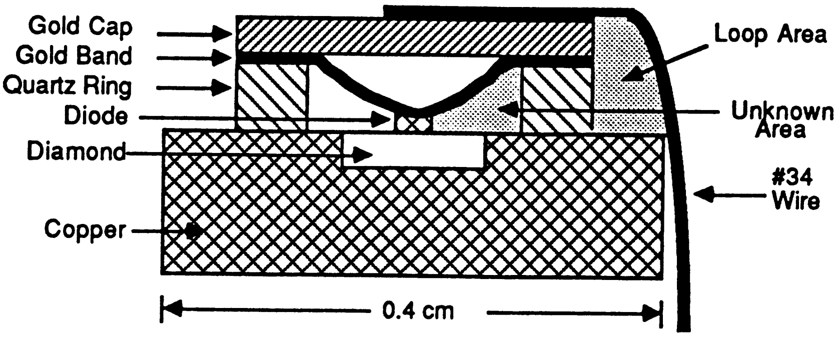

Figure 3. IMPATT diode package configuration with coupling loop, adapted from Kuno.[4]

Experimental results

The combiner design allowed for 21 diode rod assemblies, as in Fig. 2, spaced 9.2 mm center to center in a modified rectangular pattern. Each rod was embedded in a 4x4x0.5 inch copper plate, as shown in Fig. 4. The plate served as the cavity plane reflector and an effective heat sink. The diode spacing was taken from Mink[1], which gives normalized source spacing with respect to fractional mode power and driving point resistances for various array sizes. He concluded that efficient coupling could be expected in the transverse fundamental mode when the diodes were properly spaced. The ultimate goal is to combine many individual diodes to obtain one high power source. Theory predicts that if a single diode couples 1 mW of rf power into the fundamental mode of a quasi-optical power combiner, then, with diode spacing and cavity dimensions held constant, a 5x5 array of diodes would combine to yield 300 mW, a 7x7 array - 630 mW, and a 9x9 array - 800 mW. This is satisfying on physical grounds because in the limit of few diodes their "antenna patterns" excite many modes in addition to the one coupled into the output waveguide. As the diode array begins to fill the spot size of the mode at the plane reflector, its "antenna pattern" is then coupled primarily into a single mode. Finally, as the array becomes larger than the spot size, the power radiated by the outer diodes is lost.

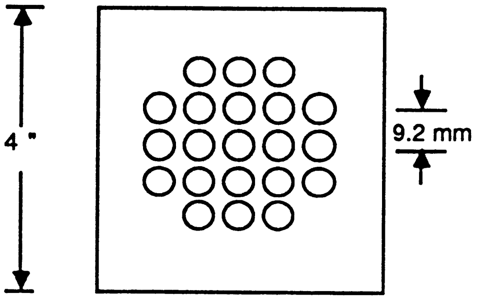

Figure 4. Planar reflector with embedded diode assemblages.

The manufacturer calibrated each diode in a standard IMPATT diode test circuit in which a diode in reduced-height waveguide is current biased and rf exits to full-height waveguide through a stepped transition section. Such a test circuit was obtained and a sample diode was found to operate at its certified operating point discussed earlier. These sources operate in a low Q mode and do not exhibit high spectral purity. Power is typically distributed across a bandwidth of several hundred kHz or more. Conversely, a quasi-optical cavity will provide a significantly higher Q. Since the spectral purity of an oscillator is related to the Q of its resonant circuit, the possibility of significantly enhanced spectral purity exists. This could be dramatically observed by changing the cavity spacing so that the Q of the modes varied. More than an order of magnitude variations in spectral purity occured and, in favorable cases, HWHM (half width at half maximum) bandwidths that approached 10 kHz were observed.

For a desired operating frequency of 60 GHz, the coupling loop area shown in Fig. 3 was calculated to be 0.4 mm^2. Teflon and enamel coated 30 to 40 gauge copper wire was tested. The diode was current biased over the complete range up to 300 milliamps. This produced rf between 40 and 45 GHz. Detectable oscillations could not be found above 45 GHz regardless of bias. Bias current ranged from 90 to 150 milliamps when rf was detected, half the nominal current for 60 GHz operation. Output power was disappointingly low. The frequency/current relationship in the 40 to 45 GHz range at these low bias currents was distinctly linear, an interesting but not a useful result for this experiment.

The disparity between calculated and observed oscillation frequency for the 0.4 mm^2 loop area is theorized to be a result of the packaging dimensions and the bias filter network. Figure 3 shows that beneath the gold cap is an area in which a gold band bridges the length of the quartz ring connecting the cap to the n$^+$ diode region. Furthermore, the band orientation beneath the cap is unknown. This unexposed area may contribute additionally to the 0.4 mm^2 loop area constructed externally to the cap and is loaded with dialectrics. Accordingly, the loop slot was milled down close to the cap to reduce the total loop area. Better impedance matching and increased radiated power were anticipated.

The results were encouraging. It was possible to achieve an order of magnitude greater output power at bias currents above 200 milliamps at a specific frequency. Lost, however, were the broad tunability characteristics previously found with larger loops and lower currents. Rather, the diode was tunable over a 700 to 800 MHz range for bias currents between 200 and 270 milliamps. It was difficult, though possible, to achieve operating frequencies as high as 42 GHz. This necessitated pressing the wire loop around the diode cap to get the smallest external loop area. Possibly owing to the variability of the unknown area beneath the cap, most diodes more easily produced radiation in the 33 to 37 GHz range. Refinements to the loop area would produce output near 35 GHz for most diodes. Number 34 gauge enamel coated wire yielded the best performance for both output power and durability. With a Hewlett-Packard 8555 spectrum analyzer, high spectral purity was observed even when the cavity length was reduced to a few inches. At the designed length of 10 inches, the loaded cavity Q was measured to be 5000. For a single oscillating diode in this configuration, spectral purity was measured at 50 kHz HWHM bandwidth.

Frequency, bias current, and loop area were defined for several diodes and the quest to phase couple two and more diodes in the cavity was launched. Ka band (26.5 - 40 GHz) waveguide replaced the V band waveguide to accomodate the newly selected 35 GHz region of operation. A wavemeter, crystal detector, oscilloscope, and spectrum analyzer were connected to measure the frequency and power of the diode. Two diodes were selected and their loop areas were adjusted for operations near 35 GHz. When within 1 GHz of each other, they became candidates for coupling in the combiner. Coupling with two diodes was not spontaneous, but easily achieved by alternately adjusting the bias current and cavity length. Precise current tuning was achieved with precision potentiometers. Cavity length was adjusted with a micrometer-driven translation table on which the plane reflector was mounted. The activity was easily monitored from either the dc level on the scope or on the spectrum analyzer. Once the diodes were coupled, the spectrum analyzer revealed that they remained so despite varying bias current by as much as 5%. Coupling enhanced spectral purity which was measured to be 25 kHz HWHM bandwidth. In combination, two diodes produced about four times more power than the individual diodes, in agreement with theoretical predictions. A third diode was prepared in a similar fashion and bias tuned to near the operating frequency of the first two diodes. Phase locking of this third diode was straight forward. It is expected that the rest of the array can be filled in by continuing this process.

Conclusions

Power combining with millimeter wave IMPATT diodes in a quasi-optical cavity has been demonstrated. Power exceeding merely the sum of the individual diode outputs has been observed as predicted. The diodes oscillating in a high Q quasi-optical cavity produce radiation of high spectral purity. Formidable obstacles still exist in understanding impedance matching of wire loop coupled antennas to IMPATT diodes. Inherent variablity in commercially packaged IMPATT diodes has complicated the theoretical calculation of oscillating frequencies due to the introduction of unknown coupling loop geometries. These problem areas may eventually be overcome by epitaxially growing diodes on a single substrate and fabricating coupling loops to precise dimensions with microstrip techniques to produce a large array of millimeter wave diodes in a monolithic integrated circuit.

Acknowledgements

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