A W-Band Overmoded-Waveguide Oscillator With Gunn Diodes

Jongsuck Bae, *Senior Member, IEEE*, Masayuki Fujita, and Koji Mizuno, *Fellow, IEEE*

***Abstract*—Spatial power combining of Gunn diodes having an efficiency of greater than 80% has been demonstrated at W-band using an overmoded-waveguide resonator having an array of fundamental mode (TE_{10}) waveguides. Nine Gunn diodes contained in the 3×3 TE_{10}-waveguide array have oscillated in a single TE_{30} mode in the overmoded-waveguide resonator, and have produced 0.45-W output power (continuous wave) with a combining efficiency of 55% at 98.8 GHz. This efficiency has been improved to 84% using a small and compact resonator that reduces the number of undesirable modes in the overmoded waveguide. The output mode of TE_{30} in the oscillator has been converted to TE_{10} using a mitered-waveguide junction mode converter.**

***Index Terms*—Millimeter-wave oscillators, power combiners, waveguide arrays.**

I. Introduction

Spatial power combining of solid-state devices is a potential technique for generating coherent and intense millimeter waves, particularly at high frequencies above 90 GHz [1]–[3]. Various power combiners having output powers of greater than 1 W have been demonstrated [4]–[9]. However, these power combiners continue to be operated at frequencies below 60 GHz. In order to achieve highly efficient spatial power combining at short millimeter wavelengths, an overmoded-waveguide oscillator has been developed [10].

The oscillator consists of an array of fundamental-mode (TE_{10}) waveguides containing solid-state devices, a metal overmoded-waveguide, and a sliding short (see Fig. 1). The horn couplers at the ends of the TE_{10}-waveguides convert the $m \times n$ TE_{10} modes in the waveguide array to the TE_{m0} mode in the overmoded waveguide with a theoretical efficiency of 100%. This perfect mode matching enables the devices to oscillate efficiently in the single TE_{m0} mode in the resonator. The overmoded waveguide is a low-loss transmission line even at frequencies above 100 GHz [11], and the waveguide-based resonator provides sufficient heat sink for a large number of devices. Therefore, the overmoded-waveguide oscillator can produce high power at high efficiency for short millimeter wavelengths. Experiments performed at V-band demonstrated that the overmoded-waveguide oscillator can achieve an efficiency of greater than 80% and an output power of 1.5 W [continuous wave (CW)] using nine Gunn diodes at 61 GHz [9].

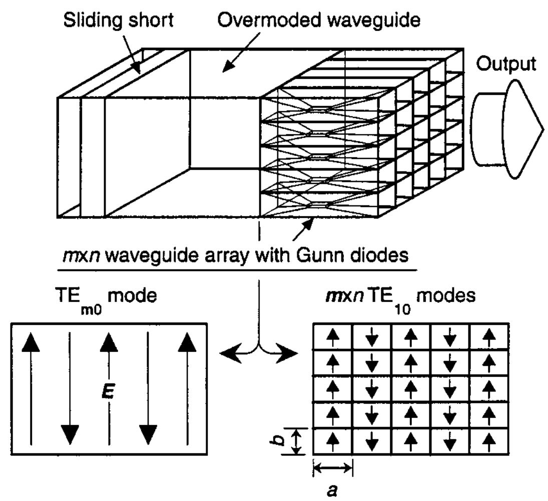

Fig. 1. Configuration of the overmoded-waveguide oscillator with Gunn diodes, and mode conversion between the $m \times n$ TE_{10}-mode array and the TE_{m0} mode in the overmoded-waveguide resonator.

This paper introduces an overmoded-waveguide Gunn diode oscillator developed at the 94-GHz band. An efficient and wide-band mode conversion of the output mode in the oscillator to the fundamental mode is also demonstrated using a waveguide-circuit technique.

II. Resonator Design

The design method for the W-band overmoded-waveguide oscillator is similar to that for the V-band oscillator. In Fig. 1, for the TE_{m0} mode of operation, the overmoded waveguide acts as a TE_{10}-mode waveguide formed by the horn aperture. This simplifies the equivalent circuit for the oscillator, as shown in Fig. 2. Z_{10} and Z_{w10} are the characteristic impedance of the TE_{10} waveguides, X_L and X_C are reactance of a bias post, k_{p1} is a post-coupling factor, and Z_G is the impedance of the Gunn diode. L is the spacing between the horn array and the sliding short. The parameters X_L, X_C, and k_{p1} are calculated using the induced electromotive force (EMF) method developed by Eisenhart and Khan [12]. The equivalent circuit in Fig. 2 is very similar to those of conventional waveguide resonators containing Gunn diodes. Consequently, we can use a number of conventional waveguide techniques to design the overmoded-waveguide oscillator [13]–[15].

In Fig. 2, the operation impedance of the Gunn diodes, i.e., Z_G, must be determined in order to design the oscillator. However, accurate measurement of Z_G of high-power W-band

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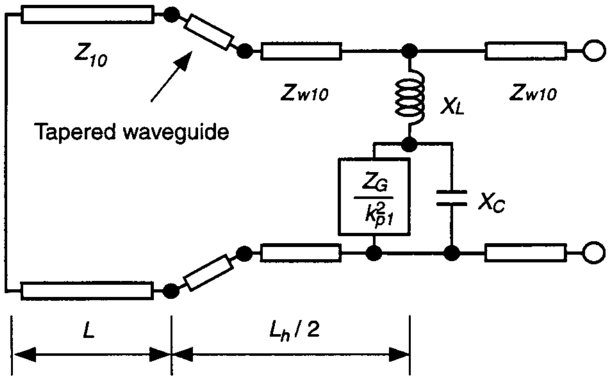


Fig. 2. Equivalent circuit for the overmoded-waveguide oscillator.

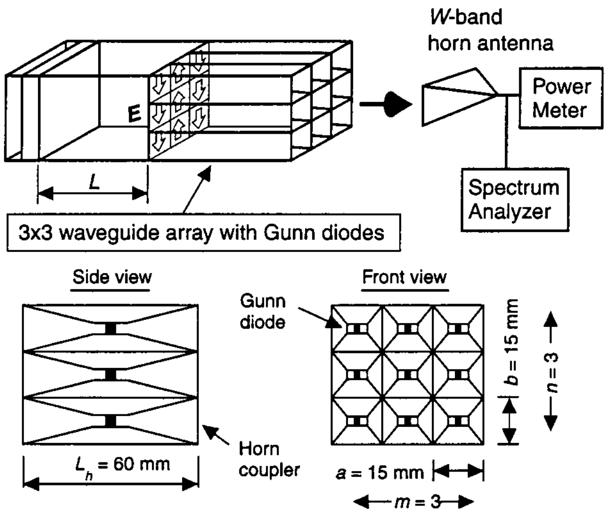


Fig. 3. Experimental setup.

Gunn diodes is difficult using conventional methods [16]. Therefore, Z_G has been approximated via the following procedures. First, the oscillation frequencies and power of each of the diodes are measured experimentally using a test waveguide resonator, which consists of a standard W-band waveguide and a backshort. Next, the impedance Z_C of the test resonator looking from the diode is calculated using the EMF method. Finally, Z_G is derived from the oscillation condition $Z_G + Z_C = 0$ for the test resonator.

III. Experimental Setup

Fig. 3 shows the experimental configuration of an overmoded-waveguide oscillator having a 3 $\times$ 3 array of Gunn diodes for operation at approximately 94 GHz. The packaged Gunn diodes used in the present experiment are of an InP-type Japan Energy Company NT-W90 and operate in the fundamental mode. The maximum rated power of the diodes is approximately 90 mW in CW at 94 GHz. The TE_{10} waveguides are standard W-band rectangular waveguides and are 10 mm in length. The pyramidal horns have square apertures of dimensions $a = b = 15$ mm and a length of 25 mm. As mentioned previously, these dimensions match the electromagnetic-field distributions between the TE_{10} and overmoded waveguides. The larger size of the horn aperture was chosen to fit the 3 $\times$ 3 waveguide array to the overmoded waveguide having a cross section of 45 mm $\times$ 45 mm, which is identical to that used in the V-band oscillator. The effect of the dimensions of the overmoded waveguide upon power-combining operation in the oscillator is discussed later in this paper. The nine Gunn diodes were biased by a single dc-power supply through disk-type posts [17], each having a diameter of 2.2 mm. The disk post decreases the impedance of the TE_{10} waveguide of full height to match that of the diode.

The oscillation frequencies and output power for the oscillator were measured using a W-band standard horn antenna connected to a spectrum analyzer (HP-8563A) and a power meter (Anritsu Company, MP4803A and ML2019). The W-band horn was placed at a distance of 1.3 m from the horn antenna array.

IV. Experimental Results

A. Gunn Diodes

The dimensions of the TE_{10} waveguides and the bias posts were determined experimentally through measurements in the test waveguide resonator. The Gunn diodes in the resonator oscillated with power ranging from 50 to 70 mW at frequencies between 91 and 97 GHz. The evaluated admittance of the Gunn diodes has been changed in the ranges of (-0.5, -27) mS in conductance and of ($+j22$, $-j5$) mS in susceptance. The admittance of approximately ($-0.5 + j6$) mS has been estimated for the operation power of 70 mW at 94 GHz. These admittances have been used to estimate the oscillation frequencies in the overmoded-waveguide resonator.

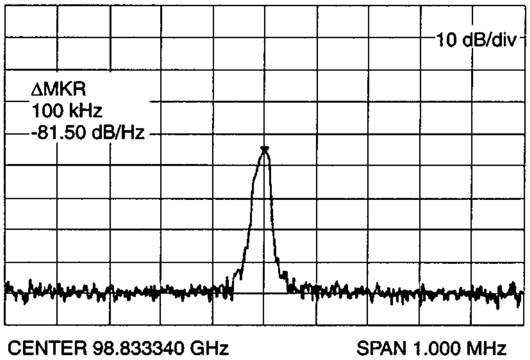
B. TE_{30} Mode of Operation

Fig. 4(a) and (b) shows a comparison of the measured frequency spectra for the oscillators and one diode [see Fig. 4(a)] and nine diodes [see Fig. 4(b)] at 98.8 GHz. The measured C/N ratios for the oscillators are -81.5 dBc/Hz at a 100-kHz offset for the one-diode case and -91.3 dBc/Hz for the nine-diode case. The C/N ratio reduction indicates that power from the nine diodes has been successfully combined coherently in the overmoded-waveguide resonator.

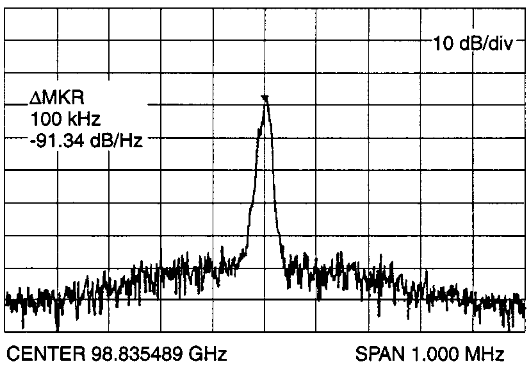
From the operation principle of the overmoded-waveguide oscillator, the number m of TE_{10} waveguides in the H-plane determines the oscillation mode. For $m = 3$, the oscillation mode is TE_{30}. This theoretical prediction has been confirmed by comparing theoretical and measured radiation patterns from the output horn array at 98.8 GHz, and the results are shown in Fig. 5. The solid curves indicate the theoretical radiation patterns for the TE_{30} oscillation mode. In Fig. 5, the theoretical dips at $\pm 18^\circ$ for the H-plane and at $\pm 12^\circ$ for the E-plane have disappeared in the measurements. These deviations from theory are consistent with slight differences in the actual horns from ideal TE_{10}-mode horns.

C. Oscillation Frequency and Power

Fig. 6(a) and (b) shows the measured frequencies [see Fig. 6(a)], and corresponding total output power for the oscillator in the TE_{30} mode [see Fig. 6(b)], as a function of the

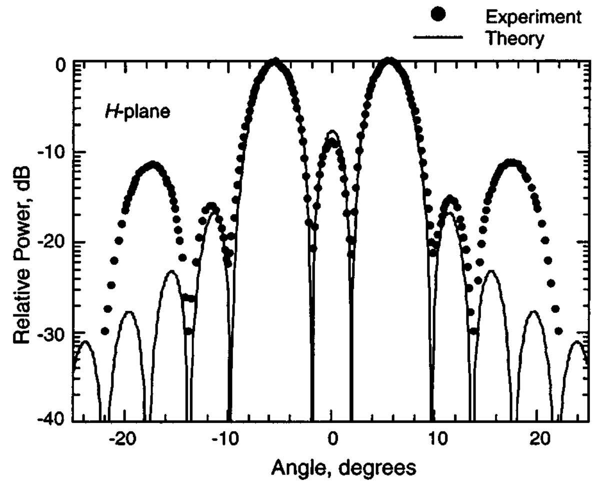


(a)

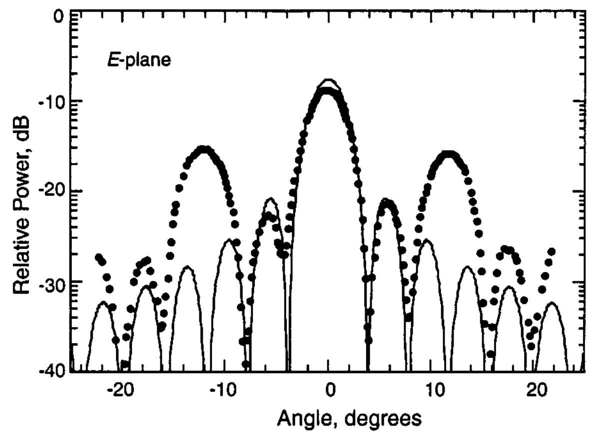


(b)

Fig. 4. Measured frequency spectra of the overmoded-waveguide oscillators with: (a) one Gunn diode and (b) nine diodes at 98.8 GHz.



(a)



(b)

Fig. 5. Measured and theoretical: (a) H- and (b) E-plane patterns of the output beam from the overmoded-waveguide oscillator in the TE_{30} mode at 98.8 GHz.

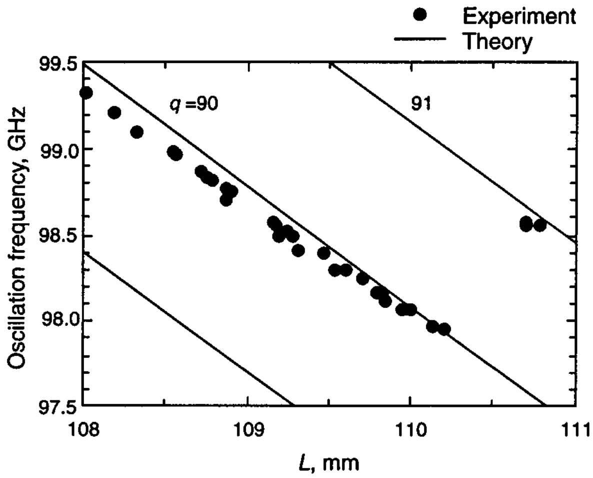
length L between the sliding short and horn array. The total output power of the oscillator was estimated from the power detected by the W-band standard horn and the theoretical radiation patterns for the TE_{30} mode. The solid lines indicate theoretical frequencies calculated using the equivalent circuit for the oscillator.

In Fig. 6(a), the theoretical frequencies are in good agreement with the measured values, even though approximate values of Z_G were used. The measured tuning frequency range is 1.3 GHz (1.3%) at a center frequency of approximately 98.5 GHz. The maximum output power is 450 mW at 98.8 GHz, which corresponds to a power-combining efficiency of approximately 55%. These results indicate that the overmoded-waveguide resonator can be used for spatial power combining of Gunn diodes at short millimeter wavelengths.

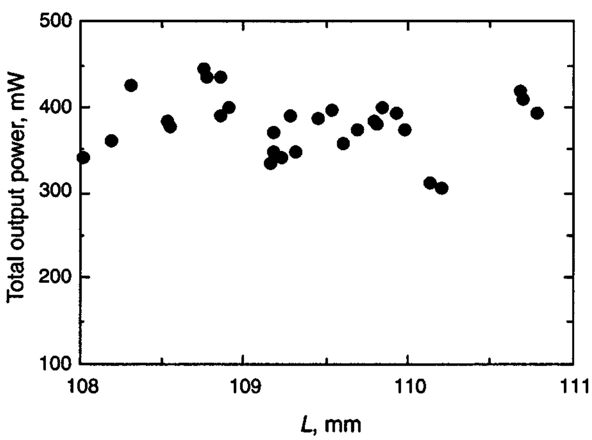
The measured efficiency and tuning range for the W-band overmoded-waveguide oscillator are small, i.e., 83% and 4.6%, respectively, compared to those obtained for the V-band oscillator [10]. The results for the W-band oscillator may have been a result of the dimensions of the resonator being too large for operation at 94-GHz band. In the overmoded waveguide having dimensions of 45 mm $\times$ 45 mm, several TE modes of greater than 25 can exist so that the TE_{30} mode of oscillation changes easily to any of the other modes with little variation in the position of the sliding short. This instability of oscillation results in the reduced efficiency. In addition, radiation waves from the 3×3 horn array having the larger apertures require a longer distance in order to form the TE_{30} mode in the overmoded waveguide. Thus, resonator lengths of greater than 100 mm are necessary for oscillation in the TE_{30} mode, as shown in Fig. 6(a). The longer resonators result in the narrower tuning frequency range.

D. Improvement of Oscillator Performance

In order to improve the oscillator performance, a small and compact overmoded-waveguide resonator was fabricated and tested for the same packaged Gunn diodes. The dimensions of the TE_{10}-waveguide array are shown in Fig. 7. The three waveguides form a unit array of 3×1, each of which has a width of 2.7 mm and a height of 0.8 mm at the center and a height of 8.2 mm at both ends. Using this waveguide array with three Gunn diodes, a combining efficiency of 84% and an output power of 227 mW at 93.8 GHz have been achieved. The tuning frequency range has been also increased from 1.3% to 3.6%. Detailed descriptions of the compact W-band oscillator are presented in the symposium digest [18]. The experimental results clearly indicate that reducing the resonator dimensions is an effective means by which to improve power-combining efficiency, as well as tuning frequency range, in the overmoded-waveguide oscillator.



(a)



(b)

Fig. 6. (a) Measured oscillation frequency and (b) total output power in the overmoded-waveguide oscillator operating in the TE_{30} mode as a function of L. Here, q is the longitudinal mode number determined by the resonator length.

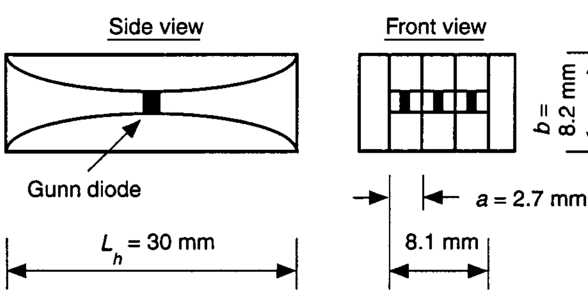


Fig. 7. Dimensions of the 3 × 1 TE_{10}-mode waveguide array.

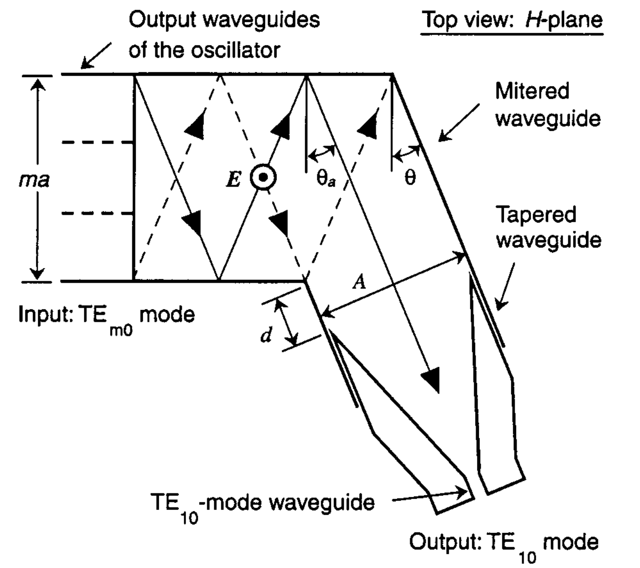


Fig. 8. Schematic drawing of the mode converter with a corner in the H-plane. Here, d is the spacing between the corner and tapered waveguide.

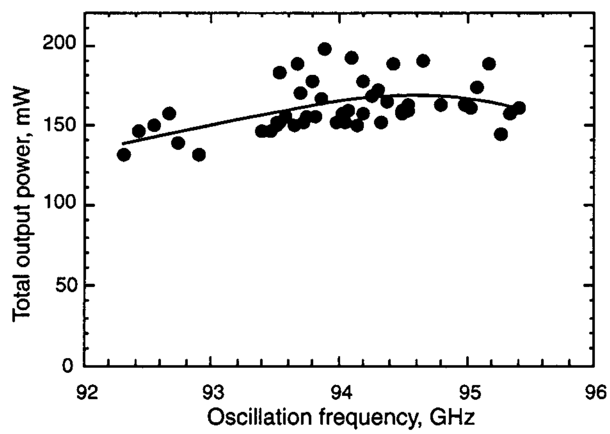


Fig. 9. Measured maximum power from the mode converter connected to the overmoded-waveguide oscillator as a function of the frequency. The frequencies have been adjusted by changing d between 0–2 mm.

V. Mode Conversion

A. Mode Conversion With a Mitered Waveguide

The output mode of TE_{30} in the overmoded-waveguide oscillator has been converted to the fundamental (TE_{10}) mode using a mitered waveguide junction [19]. Fig. 8 shows the configuration of the mode converter [20]. This mode converter consists of an oversized rectangular waveguide having a mitered waveguide junction in the H-plane and a tapered waveguide. In Fig. 8, based on the theory of rectangular waveguides, the propagation angle of the waves from the oscillator in the oversized waveguide is determined by the wavelength λ and the output horn aperture a of the oscillator, and is given by $\theta_a = \cos^{-1}(\lambda/2a)$. When the miter angle θ of the junction is equal to θ_a, the waves in the $\mathrm{TE}_{\mathrm{m}0}$ mode are converted to a quasi-plane wave, which has high power in the TE_{10} mode. Thus, the TE_{10} mode output is obtained through the tapered waveguide having a TE_{10}-mode waveguide at its end. The width of the mitered waveguide A in Fig. 8 is given by $2max\sin\theta$, where m is the mode number, i.e., the number of output horns of the oscillator in the H-plane.

B. Experimental Demonstration

The mitered-waveguide junction mode converter with $\theta = 54°$ and $A = 13$ mm was fabricated and tested for mode conversion from TE_{30} to TE_{10} in the compact W-band oscillator described in Section IV-D. The tapered waveguide has a standard W-band waveguide at its end. The taper length was chosen as 50 mm in order to obtain a power reflection coefficient of less than 10^{-4} for the TE_{10} mode at 94 GHz.

Fig. 9 shows the measured maximum power in the overmoded-waveguide oscillator with the mode converter for different frequencies between 92.5–95.4 GHz. In these experiments, the spectrum analyzer and the power meter were directly connected to the TE_{10}-mode waveguide in the tapered waveguide for measurement. The measured powers and frequencies were obtained by adjusting the positions d of the tapered waveguide (refer to Fig. 8) and of the sliding short in the oscillator.

As the results presented in Fig. 9 indicate, the measured power in the TE_{10} mode is greater than 190 mW at frequencies between 93.6–95.4 GHz. The maximum power is 197 mW at 93.9 GHz, as compared to 227 mW measured for the oscillator without the mode converter. Thus, a total efficiency for the oscillator–mode converter system is approximately 73%.

For the mode converter, simulation in HP-HFSS indicates that approximately 80% of input power in the TE_{30} mode is transferred to that in the TE_{10} mode through the mitered waveguide junction at frequencies between 92–96 GHz [18]. For the oscillator without the mode converter, the measured power-combining efficiency is 84%, as described in Section IV. Therefore, the total efficiency for the oscillator-mode converter system is expected to be approximately 67% or less. However, an efficiency of greater than 70% has been achieved, as shown in Fig. 9.

In the mode converter, the remaining 20% power in higher order modes is reflected by the tapered waveguide. Theoretical simulation results have also shown that approximately 4% of the input power is returned to the oscillator in the TE_{30} mode. Thus, the mode converter acts as an output coupler and, consequently, would increase the power-combining efficiency in the overmoded-waveguide oscillator due to a resonant effect [21]. These results indicate that the mode converter using a mitered waveguide junction is useful for high-efficiency conversion of the output mode of the overmoded waveguide oscillator to the fundamental mode in the wider frequency range.

VI. Conclusion

Overmoded-waveguide oscillators with Gunn diodes have been developed as a means for achieving highly efficient spatial power combining at W-band. A CW output power of 0.45 W at frequencies of approximately 99 GHz has been produced by an overmoded-waveguide oscillator containing nine Gunn diodes with an efficiency of 55%. This combining efficiency has been increased to greater than 80% at 94 GHz by using a small resonator having a cross section of only 8.1 mm $\times$ 8.2 mm. A mode converter having a mitered waveguide junction has been also developed for mode conversion of the output mode in the overmoded-waveguide oscillator. Experimental results have shown that, by using the newly developed mode converter, the output TE_{30}-mode in the oscillator can be converted to the fundamental mode with an efficiency of about 80% in the frequency range between 93.6–95.4 GHz. These results indicate that the overmoded-waveguide oscillator is a practical high power source at short-millimeter wavelengths.

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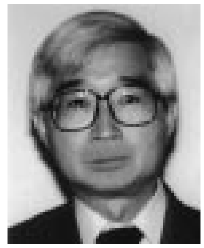

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