Spatial Power Combining of Gunn Diodes Using an Overmoded-Waveguide Resonator at Millimeter Wavelengths

Jongsuck Bae, *Senior Member, IEEE*, Takanori Unou, Tetsu Fujii, and Koji Mizuno, *Fellow, IEEE*

***Abstract*—A millimeter-wave oscillator which incorporates an overmoded-waveguide resonator with an array of TE_{10}-mode waveguides containing Gunn diodes, has been developed as a means for achieving highly efficient spatial power combining. This oscillator makes use of mode conversion of radiation power from Gunn diodes in the waveguide array to the overmoded-waveguide resonator to produce high power at millimeter wavelengths. An efficiency of about 83% and an output power of 1.5 W (continuous wave) at 61.4 GHz, has been achieved with a 3 × 3 waveguide Gunn diode array.**

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

I. Introduction

QUASI-OPTICAL solid-state power combining has generated a great deal of interest as a means of producing a high-power source at millimeter and submillimeter wavelengths [1]–[3]. Two-terminal devices such as Gunn and IMPATT diodes can be used to produce several tens of milliwatts, even at frequencies above 100 GHz. Thus, combining power from 20 of these diodes or less could produce enough RF power for many practical applications at millimeter wavelengths.

Mink described that, in a quasi-optical resonator, source elements of more than 5×5 in a regular rectangular array were needed to decrease diffraction losses and to achieve a mode-conversion efficiency of more than 80% for radiation power from the array to the resonator [4]. The high mode-conversion efficiency is indispensable for efficient spatial power combining. Thus, conventional quasi-optical open resonators are not suitable for a smaller array of diodes.

Closed resonators can maintain coherent confined beams and, thus, provide a more suitable means for combining power from small numbers of diodes. We have developed a new waveguide power combiner, which incorporates an array of fundamental-mode waveguides with Gunn diodes, inside of an overmoded-waveguide resonator, in order to avoid diffraction losses and to achieve a mode-conversion efficiency of 100%. In this paper, the overmoded-waveguide Gunn diode oscillator with a power-combining efficiency of more than 80% at millimeter wavelengths is presented.

Manuscript received March 24, 1998; revised August 27, 1998. This work was supported in part by the Ministry of Education, Science, Sports, and Culture under Grant-in-Aid for Scientific Research (B) 09450134, 1998, Japan.

J. Bae, T. Unou, and K. Mizuno are with the Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan.

T. Fujii was with the Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan. He is now with the New Japan Radio Company, Ltd., Saitama 356-8510, Japan.

Publisher Item Identifier S 0018-9480(98)09208-4.

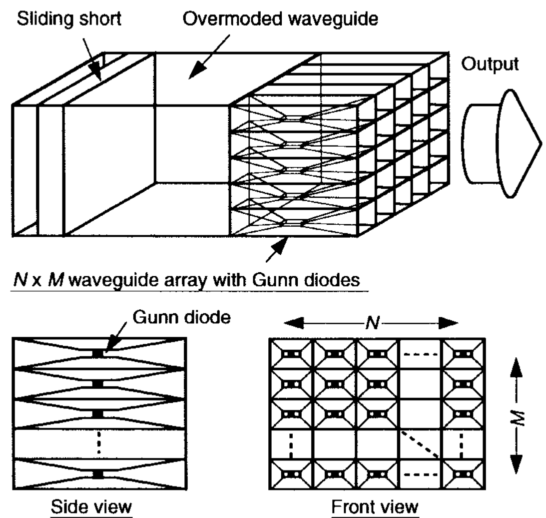


Fig. 1. Configuration of the overmoded-waveguide oscillator with Gunn diodes.

II. Resonator Configuration

Fig. 1 shows the configuration of an overmoded-waveguide oscillator with diode devices. The oscillator consists of an $N \times M$ array of fundamental-mode (TE_{10}) waveguides with pyramidal horn couplers at both ends [5], a metal overmoded waveguide with a cross section of greater than an operating wavelength, and a sliding short. The diode devices (in our case, Gunn diodes) are mounted at the center of the TE_{10}-mode waveguides and are biased by a dc-power supply through an insulated metal post.

The resonator configuration in Fig. 1 allows the oscillator to operate in a single mode even though an overmoded waveguide is used as a resonator. Referring to Fig. 2, the $N \times M$ TE_{10}-mode array transfers energy selectively to the TE_{N0} mode in the overmoded waveguide through the horn couplers with conversion efficiency of 100% because their electric and magnetic fields at the boundary between the horn array and overmoded waveguide are exactly the same.

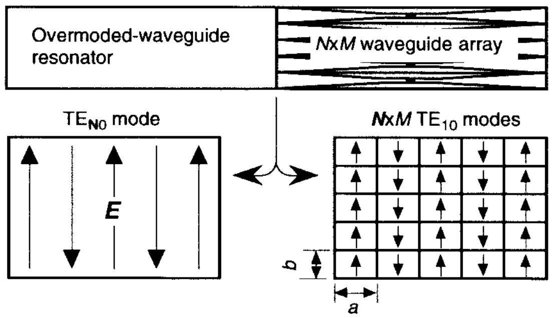


Fig. 2. Mode conversion between the $N \times M$ TE_{10} mode array and the $\mathrm{TE}_{\mathrm{N}0}$ mode in the overmoded-waveguide resonator.

The other modes in the overmoded waveguide, such as the TE_{10} mode, are strongly suppressed by the TE_{10}-waveguide array because their mode-conversion efficiencies are very low compared to that for the $\mathrm{TE}_{\mathrm{N}0}$ mode. For instance, in the case of a 3 $\times$ 3 horn array, the mode-conversion efficiency is only 68% for the TE_{10} mode in the overmoded waveguide. The other modes have efficiencies lower than that for the TE_{10} mode. These mode-conversion efficiencies were theoretically estimated by calculating mode matching of a TE_{l0} mode (l: an integer) in the overmoded waveguide with the 3 $\times$ 3 TE_{10} mode array, assuming that there was no reflection at the boundary between the horn array and the overmoded waveguide.

The overmoded-waveguide resonator not only improves efficiency, but also provides a large heat sink for the Gunn diodes, which have a low dc–RF conversion efficiency of 6% or less. Therefore, the overmoded-waveguide power combiners can be used to achieve high output power with a high combining efficiency at millimeter wavelengths.

III. Equivalent Circuit

Fig. 3 shows the equivalent circuit developed for the overmoded-waveguide oscillator. When the oscillation mode in the resonator is $\mathrm{TE}_{\mathrm{N}0}$, the propagation constant in the overmoded waveguide matches that of the TE_{10} waveguide formed by the horn aperture. The attenuation constants do differ: in the overmoded waveguide, the attenuation constant is decreased by $1/N$ times compared to that in the TE_{10} waveguide. The overmoded-waveguide resonator acts, therefore, as a TE_{10} waveguide with a smaller propagation loss. Consequently, we can apply the same equivalent circuit-design techniques used for conventional waveguide resonators containing Gunn diodes [6], [7].

In Fig. 3, the characteristic impedance Z_{W10} of the fundamental-mode waveguide is converted to Z_{10} of the TE_{10} waveguide in the overmoded waveguide through the tapered transmission line, which corresponds to the horn couplers. L is the length between the horn array and sliding short, X_L and X_C are reactances of the bias post, and $Z'_G = Z_G/(k_{p1})^2$, where Z_G is the impedance of the Gunn diode and k_{p1} is a post-coupling factor. The parameters k_{p1}, X_L, and X_C are calculated using the induced electromotive force (EMF) method [6]. L_{effect} is an effective resonator length between the Gunn diode and sliding short. An effective length of the tapered transmission line is calculated by integrating phase changes of a wave propagating in small steps along the horn length.

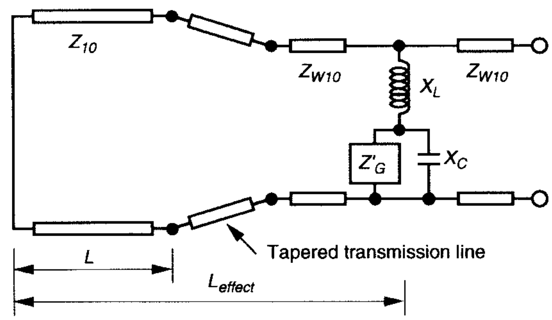


Fig. 3. Equivalent circuit for the overmoded-waveguide oscillator.

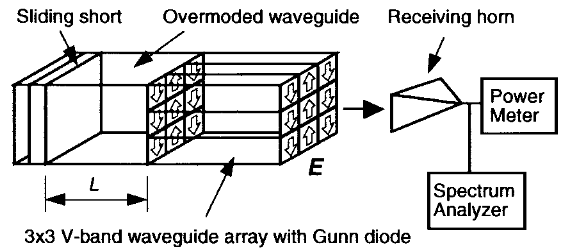


Fig. 4. Experimental setup.

IV. Experimental Setup

Fig. 4 shows the experimental configuration of an overmoded-waveguide oscillator with a 3 $\times$ 3 array of Gunn diodes for operation around 60 GHz. The Gunn diodes used are of an InP-type, Japan Energy Company, NT-V140, and have a maximum rated output power of 200 mW in continuous wave (CW) at 60 GHz. The TE_{10} waveguides with the horns have a total length of 80 mm and inner dimensions of 3.76 mm $\times$ 1.2 mm. As mentioned in Section III, the horns are necessary to match the electromagnetic-field distributions between the fundamental mode and overmoded waveguides. The pyramidal horns have square apertures with dimensions of $a = b = 15$ mm (see Fig. 2), and the length was chosen as 35 mm to obtain a power reflection coefficient of less than 2 $\times$ 10^{-3} for the TE_{10} mode at 60 GHz. The size of the horn aperture was chosen to provide enough space for mounting the packaged diode and the bias post in the waveguide. The cross section for the overmoded waveguide is 45 mm $\times$ 45 mm, which allows it to contain the 3 $\times$ 3 array of TE_{10} waveguides. The nine diodes were biased by a single dc-power supply through the circular metal posts, each with a diameter of 1.8 mm.

The oscillation frequencies and output power for the oscillator were measured using a V-band standard horn connected to a spectrum analyzer (HP-8563A) and a power meter (Anritsu Company, MP716A and ML4803A). The receiving V-band horn was placed at a distance of 1.3 m from the horn antenna array in the oscillator.

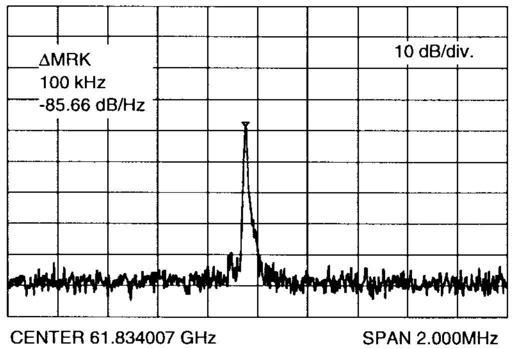


Fig. 5. Measured frequency spectrum of the overmoded-waveguide oscillator with a single Gunn diode.

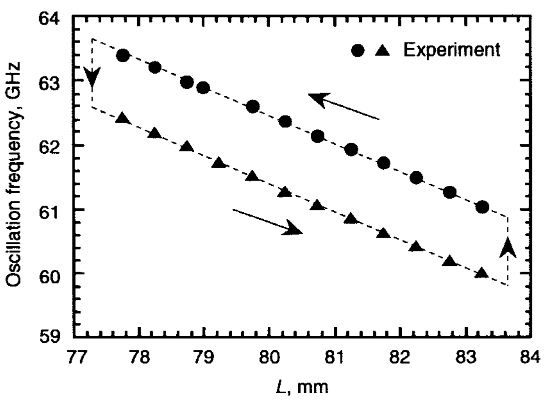


Fig. 6. Measured oscillation frequency for the overmoded-waveguide oscillator with a single Gunn diode as a function of the length L between the horn coupler and sliding short. The arrows indicate the directions of frequency changes for L's.

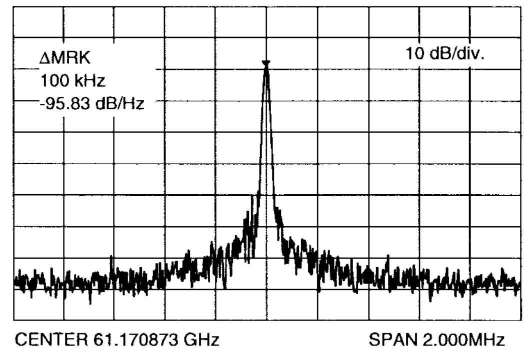


Fig. 7. Measured frequency spectrum of the overmoded-waveguide oscillator with the nine diodes.

V. Experimental Results

A. Gunn Diodes

The Gunn diodes used in the experiments can oscillate at frequencies between 54–70 GHz in conventional waveguide resonators, and have measured admittances Y_G changing from $(-19.6 - j24.4)$ mS to $(-5.4 - j22.5)$ mS at 60 GHz with their RF voltages [8]. The dimensions of the TE_{10} waveguide, including the bias post described in Section IV, were determined to satisfy the oscillation condition $Y_G + Y_c = 0$ at 60 GHz, where Y_c is the admittance of the resonator looking from the diode. Strictly speaking, Y_c's estimated using the equivalent circuit shown in Fig. 3 are valid only for the bias posts with small diameters, as described by Eisenhart and Khan [6]. However, it is believed that the equivalent circuit should provide approximate results even for the posts with a larger diameter of 1.8 mm.

In order to test the designed and fabricated overmoded-waveguide resonator, oscillation frequencies for each of the nine diodes have been measured. Fig. 5 shows the measured typical frequency spectrum for the oscillator with a single diode. A C/N ratio of −85.7 dBc/Hz at a 100-kHz offset was measured at the operating frequency of 61.8 GHz. Fig. 6 shows the measured oscillation frequencies for the same oscillator as a function of the length L between the horn array and sliding short. From Fig. 6, it is seen that the oscillation frequency has been changed between 60–63.4 GHz by adjusting L. The tunable frequency range of 3.4 GHz (5.5%) is limited due to mode hoping happening at $L = 77.7$ and 83.3 mm. Similar results were obtained for the other eight diodes. These results show that the resonator has been fabricated as designed.

B. TE_{30} Oscillation Mode

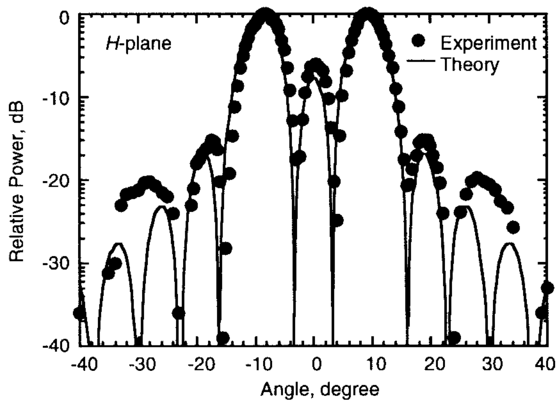
Fig. 7 shows the measured frequency spectrum for the overmoded-waveguide oscillators with the nine diodes at 61.2 GHz. The measured C/N ratio is −95.8 dBc/Hz, which is compared to -85.7 dBc/Hz measured for the oscillator containing a single diode. The C/N ratio reduction indicates that power from the nine diodes was successfully combined coherently in the overmoded-waveguide resonator.

In order to confirm the TE_{30} oscillation mode, radiation patterns from the output horn array were measured. The measured radiation patterns for H- and E-planes are shown in Fig. 8. The oscillation frequency was 61 GHz. The solid curves indicate the theoretical radiation patterns for the TE_{30} oscillation mode. The measured and theoretical powers are normalized to the peak power at an angle of 9°. The theoretical radiation patterns give good agreement with the measured patterns, except at powers of less than -20 dB, and at angles beyond ±30° for the H-plane and ±20° for the E-plane. These deviations from theory are consistent with slight differences in the actual horns from ideal TE_{10}-mode horns. The results are sufficient to show that the oscillation mode in the overmoded-waveguide oscillator is TE_{30}.

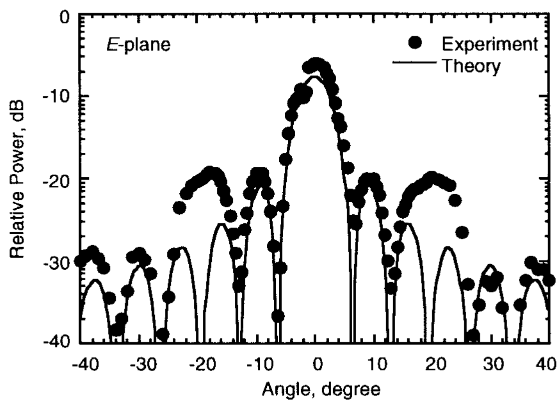
C. Oscillation Frequency and Power

The total output power of the oscillator was estimated from the power detected by the V-band standard horn and the theoretical radiation patterns for the TE_{30} mode. For estimation of the total power, the antenna gain (23.3 dB at 61 GHz) of the receiving V-band horn was taken into account. The difference between the theoretical and measured radiation patterns in Fig. 8 was ignored, as it only accounted for a 3% underestimation of total power. In Fig. 8, the detected power at 9° was 13 mW, which was estimated to correspond to a total output power of 1.42 W.

Fig. 9(a) shows the measured frequencies, while (b) shows the corresponding total output power for the oscillator in the

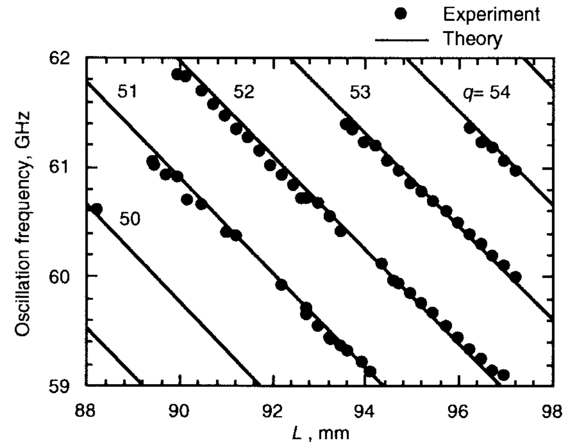


(a)

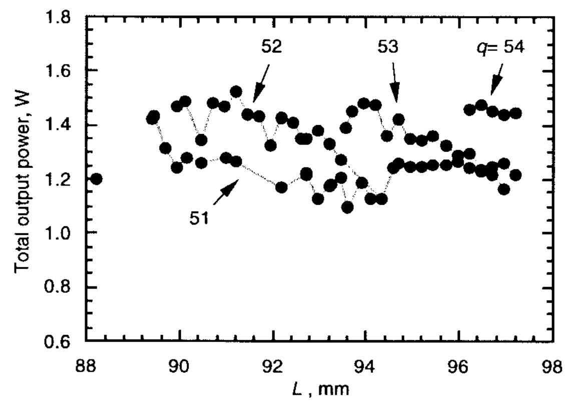


(b)

Fig. 8. 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 61 GHz. The radiation angles are measured from the center of the surface of the output-horn antenna array.



(a)



(b)

Fig. 9. (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. In the figure, q is the longitudinal mode number determined by the effective resonator length L_{effect} corresponding to L.

TE_{30} mode, as a function of L. The solid lines indicate theoretical frequencies calculated using the equivalent circuit shown in Fig. 3. In Fig. 9, two or three measured points are given at the same L. This is due to mode hoping, and hysteresis effects happened with change in the direction of travel of the sliding short [9].

In Fig. 9(a), the theoretical frequencies agree with measurements within 0.3%. The measured tuning frequency range is 2.8 GHz (4.6%) about a center frequency of 60 GHz. This tuning range is somewhat smaller than that in the oscillator with a single diode. The reason for this would be due to small differences among the oscillation characteristics of the nine Gunn diodes in the resonator. However, these experimental results indicate that the overmoded-waveguide oscillator can achieve a wider mechanical tuning range compared to conventional circuit combiners [10], [11].

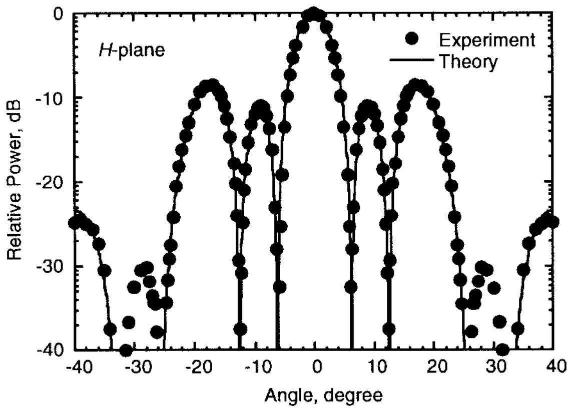
In Fig. 9(b), the total output power is larger than 1 W for all frequencies measured between 59–62 GHz. The maximum output power is 1.5 W at 61.4 GHz, demonstrating a power-combining efficiency of about 83%. The overall dc-to-RF conversion efficiency of the oscillator is 4.7%. It should be noted that the TE_{30} mode is the dominant oscillation mode in the oscillator. Oscillation in other modes was occasionally observed, but the power for these oscillations was quite small compared to that for the TE_{30} mode.

D. Mode Conversion

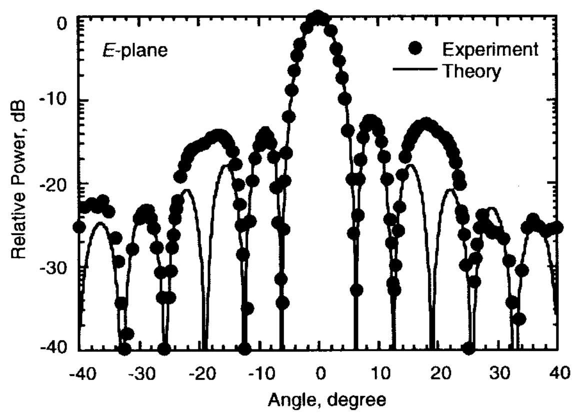
The output radiation pattern from the overmoded-waveguide oscillator, shown in Fig. 8, can be changed by controlling phases of radiation waves from the output horns.

In order to demonstrate this, π-phase shifters (Teflon plates) were inserted in the three TE_{10} waveguides in the central row of the output horn array. The phase shifters delay wave propagation in the TE_{10} waveguides by π-radians so that the nine output horns can operate in the same phase, even though the oscillation mode in the resonator is TE_{30}.

Fig. 10 shows the measured radiation patterns for H- and E-planes from the oscillator with the π-phase shifters at 61.4 GHz. The solid curves indicate the theoretical radiation patterns, which agree with measurements, except for powers detected at angles around ±30° for the H-plane and ±20° for the E-plane. The reason for the deviations from the theoretical is the same as for the results in Fig. 8. A total power radiated from the horn array was estimated to be 1.4 W, which was compared to 1.5 W from the oscillator without the phase shifters. From Fig. 10, it is seen that the strong main beam is produced at 0° by the phase shifters. It should be noted that this main beam is almost a fundamental Gaussian beam with a small diffraction angle of 4.3° and a



(a)



(b)

Fig. 10. Measured and theoretical (a) H-plane and (b) E-plane patterns of the output beam from the overmoded-waveguide oscillator with the phase shifters at 61.4 GHz. The measured and theoretical powers are normalized to the peak power at 0°.

power of about 920 mW. These results imply that the output horns in the oscillator can act as a phased antenna array. When electronically controlled phase shifters such as varactor and p-i-n diodes are used, scanning or modulating output beams from the oscillator can be possible. In addition, for some applications using this oscillator in guided-wave systems, the TE_{30} mode can be easily converted to TE_{10} through waveguide circuit techniques.

VI. Conclusion

We have demonstrated the use of an overmoded-waveguide resonator with a fundamental-mode waveguide array as a coherent power combiner with millimeter-wave solid-state devices. An overmoded-waveguide oscillator with nine Gunn diodes was used to produce 1.5 W of CW output power with a combining efficiency of 83% and a C/N ratio of -95 dBc/Hz at a 100-kHz offset for operating frequencies near 60 GHz. These results show that this type of oscillator is useful as a high-power millimeter-wave source.

References

[1] K. Mizuno, T. Ajikata, M. Hieda, and M. Nakayama, “Quasioptical resonator for millimeter and submillimeter wave solid-state sources,” *Electron. Lett.*, vol. 24, pp. 792–793, June 1988.

[2] Z. B. Popovic, M. Kim, and D. B. Rutledge, “Grid oscillators,” *Int. J. Infrared Millim. Waves*, vol. 9, pp. 647–654, July 1988.

[3] H. Kondo, M. Hieda, M. Nakayama, T. Tanaka, K. Osakabe, and K. Mizuno, “Millimeter and submillimeter wave quasi-optical oscillator with multi-elements,” *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 472–478, May 1992.

[4] J. W. Mink, “Quasi-optical power combining of solid-state millimeter-wave sources,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 273–279, Feb. 1986.

[5] J. Bae, T. Uno, H. Mazaki, T. Fujii, F. Takei, and K. Mizuno, “A horn antenna coupled quasioptical oscillator with Gunn diodes at millimeter wavelengths,” in *22nd Int. Infrared Millimeter Waves Conf. Dig.*, 1997, pp. 247–248.

[6] R. L. Eisenhart and P. J. Khan, “Theoretical and experimental analysis of a waveguide mounting structure,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 706–719, Aug. 1971.

[7] K. Chang and R. L. Ebert, “W-band power combiner design,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 295–305, Apr. 1980.

[8] J. Bae, Y. Aburakawa, H. Kondo, T. Tanaka, and K. Mizuno, “Millimeter and submillimeter wave quasioptical oscillator with Gunn diodes,” *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 1851–1855, Oct. 1993.

[9] R. L. Eisenhart and P. J. Khan, “Some tuning characteristics and oscillation conditions of a waveguide-mounted transferred-electron diode oscillator,” *IEEE Trans. Electron Devices*, vol. ED-19, pp. 1050–1055, Sept. 1972.

[10] K. J. Russell, “Microwave power combining techniques,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 472–478, May 1979.

[11] Y. E. Ma and C. Sun, “1-W millimeter-wave Gunn diode combiner,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 1460–1463, Dec. 1980.

Jongsuck Bae (M’94–A’95–SM’98) was born in Nagoya, Japan, in 1953. He received the B.Eng. degree in electric engineering from the Korean University, Tokyo, Japan, in 1976, and the D.Eng. degree in electronic engineering from Tohoku University in 1990.

In 1977, he joined the Research Institute of Electrical Communication, Tohoku University, Sendai, Japan, where he has been Associate Professor since 1992. His research has been in developing quasi-optical components such as oscillators, modulators, and couplers used for millimeter and submillimeter wavelengths and their applications.

Dr. Bae is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan, and the Japan Society of Applied Physics.

Takanori Unou was born in Toyota, Japan, in October 1973. He received the B.Eng. and M.Eng. degrees in electronic engineering from Tohoku University, Sendai, Japan, in 1996 and 1998, respectively.

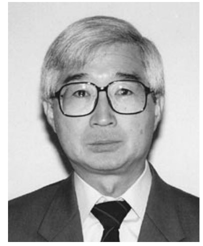
In 1998, he joined the Safety System Products Division, Denso Corporation, Kariya, Japan, where he is currently involved in research on electromagnetic compatibility in car electronics systems.

Mr. Unou is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.

Tetsu Fujii was born in Tokyo, Japan, in 1969. He received the B.Eng. and M.Eng. degrees in electrical engineering from Tohoku University, Sendai, Japan, in 1993 and 1995, respectively.

In 1998, he joined the New Japan Radio Company, Ltd., Saitama, Japan. His current research interests include coherent power combining of solid-state devices using a quasi-optical resonator in millimeter- and submillimeter-wave regions and an oscillator using resonant tunneling diodes in series.

Dr. Fujii is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.



Koji Mizuno (M'72–SM'72–F'93) was born in Sapporo, Japan, on July 17, 1940. He received the B.Eng., M.Eng., and D.Eng. degrees in electronic engineering from Tohoku University, Sendai, Japan, in 1963, 1965, and 1968, respectively.

In 1968, he joined the Department of Electronic Engineering, Faculty of Engineering, Tohoku University. He was appointed Associate Professor at the Research Institute of Electrical Communication in 1972, where, since 1984, has been a Professor of electron devices as well as a member of the Department of Electronic Engineering. In 1973, he spent a one-year sabbatical leave at Queen Mary College, University of London, London, U.K., and in 1990, spent a six-month sabbatical leave at both the California Institute of Technology, Pasadena, and Queen Mary College. In 1990, he became a Team Leader at the Photodynamics Research Center (the Institute of Physical and Chemical Research), Sendai, Japan, and is currently running a laboratory for submillimeter wave research there, as well as one at Tohoku University. He is interested in the millimeter- and submillimeter-wave region of the electromagnetic spectrum, and his current work is in detection and generation technologies and their applications within the region.

Dr. Mizuno is member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan, the Institute of Electrical Engineers of Japan, and the Japan Society of Infrared Science and Technology. He received the 17th Kagaku Keisoku Shinkokai (Scientific Measurement) Award in 1984.