# Millimeter-Wave Gaussian-Beam Antenna and Integration with Planar Circuits

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## ABSTRACT

A quasi-planar antenna, which uses a dielectrc loaded Gaussian-beam resonator is developed for 60 GHz. The resonator antenna with a Gaussian distribution of the aperture electric field is formed with a spherical and a plane mirror surfaces, which were fabricated on both sides of a plano-convex fused quartz lens with 20-mm diameter and 1.3-mm thickness. This new antenna features a very low sidelobe level (<-30 dB) and a high radiation efficiency (>90%). Antenna characteristics and integration with a mixer circuit are described.

## INTRODUCTION

Millimeter-wave components constituted mainly with waveguide technologies are considered to be replaced by MMICs in the near future. Antenna characteristic is one of the most important issues for mm-wave wireless communication systems. The transmission data rate targeted is as high as 156 Mbps, and transmitter output power is less than a few tens mW. Antennas featuring a low sidelobe level and a high radiation efficiency are required to reduce an influence of multipath propagation distortion due to reflections by walls, floors, ceilings, etc. and to secure a necessary link budget in the indoor wireless LAN systems.

The various horn antennas have good impedance characteristics over a broad frequency region; their technologies have been developed for improvement regarding sidelobe characteristics and axial symmetry. The corrugated horn having a large number of fins provided concentrically on the inner wall of a conical horn possesses an axially symmetrical beam and good cross polarization characteristics. When the height of the corrugated waveguide fins is about 1/4 wavelength, the aperture electric field distribution of the $EH_{11}$ mode is Gaussian distribution-like in the radial direction, and the excited corrugated horn exhibits a low sidelobe level and little cross polarization component. Owing to its structural complexity, a corrugated horn has many problems in terms of both fabrication technology and cost, and is used only for special purposes.

On the other hand, thin-film planar circuit technology is expanding from the microwave region into the millimeter wave region. In order to obtain high gain with a planar antenna, array antenna technology is widely used in the microwave region. In the short millimeter wave region, however, practical utilization is difficult due to a feeder loss; increasing the number of elements for obtaining a sharp directivity results in a rapid decrease in radiation efficiency. For dissemination of mm-wave use, a need has arisen for the development of a new antenna appropriate for integration with planar circuits.

## GAUSSIAN BEAM ANTENNA

### *A. Principle of Gaussian Beam Antenna*

An antenna with Gaussian distribution of the aperture electric field is formed with a spherical and a plane mirrors [1]. The antenna is a new kind of mode transformer between a guided-wave mode and a Gaussian beam. Partially transparent region on a spherical mirror is provided as a coupling region with free space [2]. The region consists of one or two-dimensional conductor grid that is fine in comparison with the wavelength. The rear surface of the strip element of the plane mirror is provided with a coupling region with the transmission line. The high-frequency signal propagating in the transmission line passes through the coupling region induces high frequency current in the strip element consisting one part of the conducting plane mirror. The induced high-frequency current on the strip element is radiated within the resonator so that the waves reflected from the two mirror surfaces repeatedly superimposed. A stable electromagnetic field distribution is formed along





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the axis by the condensing action of the spherical mirror when the interval between two mirror produces a phase difference that is integral multiple of $2\pi$. A resonant mode is manifested as a Gaussian beam in which the energy distribution of the electromagnetic waves is high near the optical axis in the direction of electro-magnetic wave propagation, and decreases rapidly with separation from the axis. A large electromagnetic field energy is accumulated in the fundamental Gaussian mode TEMooq (q+1 indicates the longitudial mode number). As a part of it a radiation power equal to the high -frequency signal supplied from the transmission line to the coupling region is released from the circular partially transparent mirror surface region. The region for coupling with free space is radiated into space in the form of a Gaussian beam. The antenna is in principle a low sidelobe antenna because the aperture surface power distribution thereof is Gaussian. [3][4]

The shape of a fundamental Gaussian beam is generally specified by the minimum spot size, $W_0$, and its location. The $W_0$ can be set by appropriately selecting the radius of curvature, $R_0$, of the spherical mirror surface and the mirror interval, D, and is given by

$$W_0^2 = (\lambda / \pi)\,[D(R_0 - D)]^{1/2} \quad (1)$$

where $\lambda$ is the wavelength of electromagnetic wave. As a widely known diffraction spread relationship, the half-apex angle, $\theta$, in the far field of a wave confined in an aperture of radius $W_0$ is given by

$$\theta = \tan^{-1}(\lambda / \pi W_0) \approx \lambda / \pi W_0. \quad (2)$$

The half-power beam width, $2\varphi$, which is usually used for an index of the antenna directivity, is given by

$$2\varphi = (2 \ln 2)^{1/2} \approx 1.18\,\theta. \quad (3)$$

***B. Radiation Efficiency of Gaussian -Beam Antenna***

The Gaussian-beam antenna can be viewed as a resonator with two ports. When the diffraction loss is negligible in comparison with losses accompanying the mirror reflections, the antenna Q value, $Q_A$, is given by

$$1/Q_A = 1/Q_0 + 1/Q_1 + 1/Q_2 \quad (4)$$

where $Q_0$ is the unloaded Q corresponding to the resistive loss of conductor mirror surfaces, and $Q_1$, $Q_2$ represent the coupling Q values which correspond to the amount of increase in loss due to the provision of the coupling regions on the mirrors. The coupling coefficients, $\beta_1$, $\beta_2$, corresponding to the coupling regions provided on the mirror surfaces can be defined as $\beta_1 = Q_0/Q_1$, $\beta_2 = Q_0/Q_2$, respectively. In the Gaussian-beam antenna, the transmittances of both reflective mirror surfaces are set high and $Q_A$ is set so as to be governed by $Q_1$ and $Q_2$, which can be represented using the reflectances of the respective mirrors, $R_1$, $R_2$, as follows

$$\begin{aligned} Q_k &= (4\pi D / \lambda)(R_k)^{1/2} / (1 - R_k) \\ &= 2\pi (q+1)(R_k)^{1/2} / (1 - R_k). \end{aligned} \quad (5)$$

Here k = 1 and 2. The resonance frequency of the fundamental mode TEMooq is given by

$$f_q = (c/2D)(q + 1 + \delta). \quad (6)$$

Here $\delta$ is the correction amount (<< 1), since the propagation of the electromagnetic waves inside the resonator is not a plane wave but a Gaussian beam. Therefore, D is approximately an integral multiple of half the wavelength. Assuming that the mirror reflectance is set at about 90 - 98 % and the longitudinal mode number inside the resonator is made 1 - 5 ( q = 0, 1, 2, 3, 4 ), $Q_A$ can achieve 30 - 1500.

The power transmittance at resonance, T, in a resonator having two ports is given by

$$T = 4\beta_1\beta_2 / (1 + \beta_1 + \beta_2)^2. \quad (7)$$

For securing a high transmittance as an antenna, the reflectances, $R_1$, $R_2$ of two mirrors must be equal, then $\beta_1 = \beta_2 = \beta$. When a highly-conductive metal is used for the mirror surfaces, $\beta$ is assumed to be a large value of 10 - 100, enabling T to be almost unity. With respect to the antenna Q value, $Q_A$ = 30 - 1500, and an antenna radiation efficiency of 95 % or higher is obtained.

## EXPERIMENT

A 60-GHz dielectric-loaded Gaussian-beam antenna (DL-GBA)was fabricated using a plano-convex fused quartz lens with 20 mm diameter, 1.3 mm thickness and 690 mm radius of curvature. Metal mirrors were formed on both-faces of the lens by 1.3μm-thick sputtered copper films. For coupling with free space, a 18-mmϕ circular region of two-dimensional grid with a metal width, *d'*, of 0.14mm and a spatial period, *a*, of 0.5mm was made on a spherical mirror surface. In this experiment, waveguide feed was used to measure antenna characteristics. For coupling with the waveguide, a 6-mmϕ circular coupling region of one-dimensional grid with *d'* of 0.23mm and *a* of 0.7mm was made on a plane mirror surface.

The 60-GHz DL-GBA was mounted on a metal block for feeding through a WR-15 waveguide with a UG-385/U flange, as shown in Fig. 1. The return loss was measured by using HP8510C. As is shown in Fig.2, the matching condition was obtained at 57.2 GHz with a 10 dB down bandwidth of 220 MHz. The antenna directivity was measured in the unechoic chamber by using a precision rotation stage for the optical use. The H-plane pattern was a Gaussian beam with a low sidelobe level of less than -30 dB, as is shown in Fig. 3. The experimental directive gain was deduced theoretically by considering a Gaussian profile with an experimental spot-size. The absolute gain was determined by comparing with the case of the standard gain horn measurement. The results are summerized in Table 1. A radiation efficiency higher than approximately 90% was achieved.

## INTEGRATION WITH PLANAR CIRCUITS

For a mm-wave antenna application, a plano-convex lens made of a low-loss dielectric material can be used to form a Gaussian beem resonator with a half wavelength. In such a configuration, a metallized mirror and active planar circuits can be integrated with a layered structure on one side of the surfaces of the low-loss dielectric substrate. On the other side of the surfaces of the substrate, metal grid pattern is formed for coupling with free space. In mm- and submm-wave regions, the DL-GBA is a quasi-planar structure, which is appropriate for integration with planar circuits for a compact transmitter/receiver. Further (5) the Gaussian-beam antenna is a resonant antenna with low insertion loss so that when used as an antenna for a high-power transmitter a strong suppressing effect with respect to unnecessary spurious can be expected. There can be realized an ultra-low spurious, low-noise antenna which prevents the local signal of a receiver from leaking the antenna and being radiated into space as an unnecessary wave. Fig.4 shows an integrated Gaussian beam antenna with a 12GHz HEMT mixer. By using a feature of a band selective antenna with low insersion loss, a new direct demoduration from rf to base-band can be expected. Many new application fields of the Gaussian-beam antenna can be anticipated.

## CONCLUSION

We presented a 60-GHz Gaussian-beam antenna fabricated by dielectric loading. The measured data exhibits a low sidelobe level and a radiation efficiency higher than approximately 90%. The antenna conducts transformation between a guided-wave mode and a resonator mode. By readily enlarging the effective aperture, a high-gain antenna can be realized. This new resonator antenna can be used in the mm- and submm-wave regions as an antenna with high radiation efficiency, band selective and suitable for integration with planar circuits.

## REFERENCES

[1] T. Matsui and M. Kiyokawa, "Gaussian-beam antenna", *International Conference on Millimeter and Sub-millimeter Waves and Applications*," Jan. 10-14, 1994, San Diego, CA, Conf. Digest p609, SPIE Vol.2250, 1994.

[2] T. Matsui, K. Araki and M. Kiyokawa, "Gaussian-Beam Open Resonator with Highly Reflective Circular Coupling Regions," IEEE Trans.Microwave Theory and Technique Vol.41, pp.1710-1714, 1993.

[3] G.D. Boyd and J.P. Gordon, "Confocal multimode resonator for mllimeter through optical wavelength maser," Bell Syst. Tech. J., Vol.40, pp.489-508, 1962.

[4] H. Kogelnik and T. Li, "Laser beams and resonators," Proc. IEEE, Vol.54, pp.1312-1329, 1966.

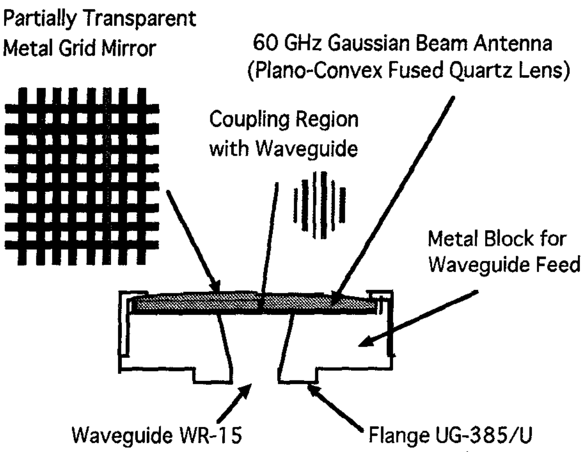


Fig.1 60 GHz dielectric loaded Gaussian beam antenna (DL-GBA) mounted on a metal block with a WR-15waveguide.

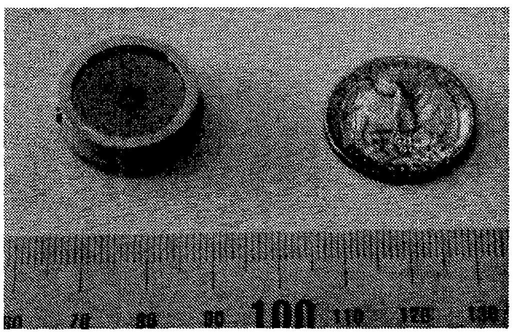

Fig2. Photograph of 60 GHz DL-GBA.

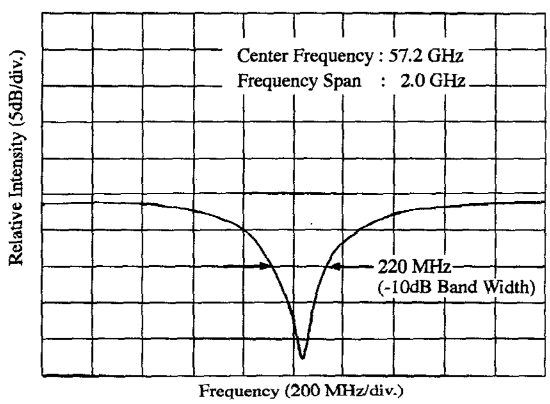


Fig.3 Return loss characteristics
10dB bandwidth : 220GHz

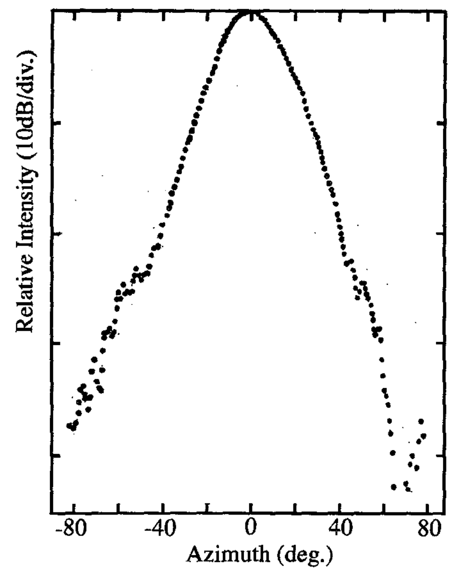


Fig.4 Antenna directivity.

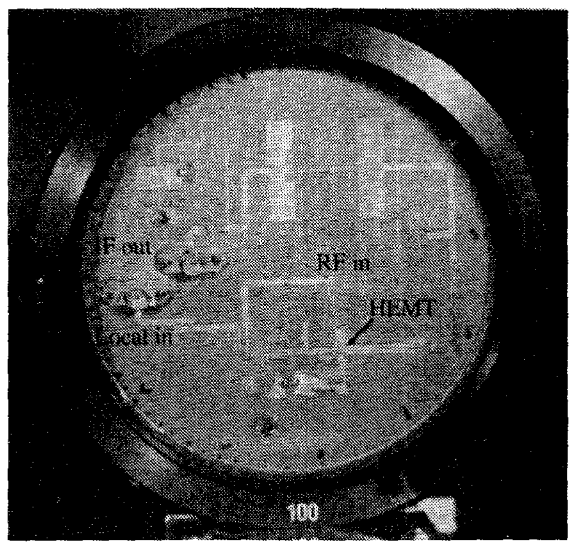


Fig.5 Integrated Gaussian beam anntena:12GHz HEMT mixer circuit is integrated behind a plane mirror.

Table 1. Summerized result of the GBA

| | Experimental | Theoretical |
|---|---|---|
| Half-power Beam Width [deg] | 25.2 ± 0.5 | 22.0 |
| Beam Spot Size [mm] | 4.25 ± 0.1 | 5.13 |
| Directive Gain [dB] | 14.2 ± 0.2 | 15.8 |
| Absolute Gain [dBi] | 14.1 ± 0.3 | 15.7 |
| Radiation Efficiency | $0.87<\eta<1.0$ | $0.95<\eta<0.98$ |