20-GHz Focusing Antennas Based on Corrugated Waveguide Scattering

Takuya Okuyama, Yasuaki Monnai, *Member, IEEE*, and Hiroyuki Shinoda, *Member, IEEE*

***Abstract*—We propose a focusing antenna based on corrugated waveguide scattering at 20 GHz. Surface waves propagating on a low-loss 1-D corrugated waveguide are scattered out of the waveguide to form a focus in the free space. The scattering is caused by a chirped grating structure incorporated on the waveguide, which is designed to involve constructive interferences at a predefined focal point. In this letter, we describe the fabrication and excitation of the antenna and experimentally demonstrate focusing at 30 cm above the structure at 20 GHz. The antenna allows for beamforming of millimeter waves with a simple planar structure.**

***Index Terms*—Focusing antennas, leaky-wave antennas, millimeter waves.**

I. Introduction

MILLIMETER-WAVE technologies have been investigated extensively for their potential in very high-speed wireless communications [1]–[3]. Moreover, taking advantage of the short wavelengths, they have been used in high-resolution sensing or imaging such as automotive radar sensors [4], contactless liquid-level measurement [5], and concealed weapon detection [6]. To attain higher spatial resolution up to the diffraction limit, a proper lens system should be employed. Yet, scaling up optical lenses toward the millimeter-wave regime results in a bulky system. A well-known method to reduce the thickness of a lens is to implement a Fresnel lens [7]–[9]. However, it still requires a huge space for free propagation between the lens and the wave source. A planar system can be implemented with microstrip arrays [10]–[12]. There, waves emitted from the source are guided along microstrip lines and radiated from patches with defined phase delays. However, the conductive losses in such a system will be severe in the millimeter-wave regime.

In this letter, we demonstrate a novel wide-aperture focusing antenna operating at 20 GHz. It is based on corrugated waveguide scattering, which has originally been presented for terahertz waves at around 0.3 THz [13]. The waveguide to be scattered is a 1-D surface waveguide with a periodically perforated corrugation [14]. A chirped grating structure incorporated on the waveguide scatters the surface waves out of the waveguide and forms a focus in free space. Here, we transfer the scheme to the millimeter-wave regime by scaling up the structure. Since the surface waves are loosely guided on a single metal layer, the waveguide is inherently low-loss, which becomes more prominent as the frequency decreases. Unlike at terahertz, coaxial cables are commonly used for millimeter waves to interconnect components. Hence, we develop a coupling scheme that directly connects coaxial cables with the corrugated waveguide. We demonstrate that the surface waves are efficiently excited from the end of a coaxial cable that is surrounded by parallel metal walls that suppress unwanted modes due to the cutoff effect.

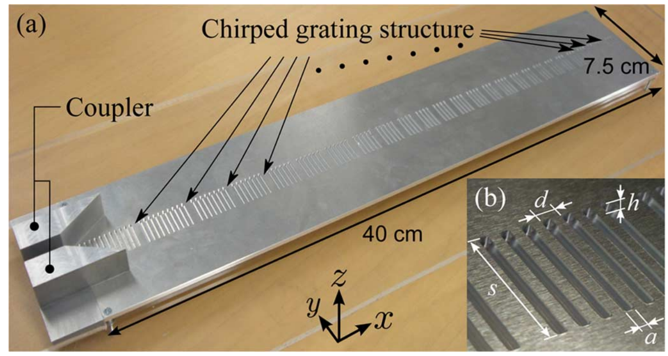

Fig. 1. Photograph of the fabricated focusing antenna. (a) Overview of the device and (b) enlarged view of the surface. The hole dimensions are as follows: $s = 15$ mm, $a = 1.35$ mm, $h = 1.2$ mm, and $d = 2.7$ mm.

The proposed antenna is regarded as a class of leaky-wave antennas. Although many periodic leaky-wave antennas have been developed for directional beamforming such as dielectric-rod leaky-wave antennas [15] or metal strips [16], [17], modifying the periodic grating into nonperiodic ones allows us to tailor the beam pattern [18]. The use of the corrugated waveguide enables designing the dispersion relation by its geometry depending on applications.

II. Device Fabrication

We fabricated a 20-GHz focusing antenna shown in Fig. 1. It is composed of a waveguide with a periodically perforated corrugation and an excitation coupler with metallic walls. The waveguide is fabricated by periodically milling rectangular blind holes on an aluminum plate. The hole dimensions are 1.35 mm in width by 15 mm in length by 1.2 mm in depth [Fig. 1(b)]. It supports loosely confined one-dimensional surface waves propagating along the hole apertures [14]. The extent of the field confinement in the vertical and the lateral directions is defined by the depth and the width of the blind holes, respectively. Since the surface wave is a slow wave, proper scatterers are required to launch the surface waves into free space. Here, we incorporate a chirped grating on the waveguide by intentionally leaving some holes unmilled. Those locally flat regions disturb

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T. Okuyama is with the Central Research Laboratory, Hitachi, Ltd., Tokyo 185-8601, Japan.

Y. Monnai, and H. Shinoda are with the Department of Information Physics and Computing, the University of Tokyo, Tokyo 113-8656 Japan (e-mail: Yasuaki_Monnai@ipc.i.u-tokyo.ac.jp).

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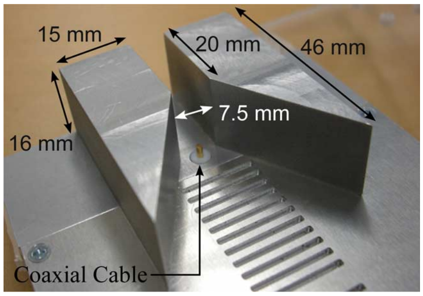

Fig. 2. Coupler to excite the waveguide from a coaxial cable. Metallic walls suppress unwanted backward radiation. An inner conductor of the coaxial cable lengthened by 2.4 mm is inserted from the backside of the aluminum plate.

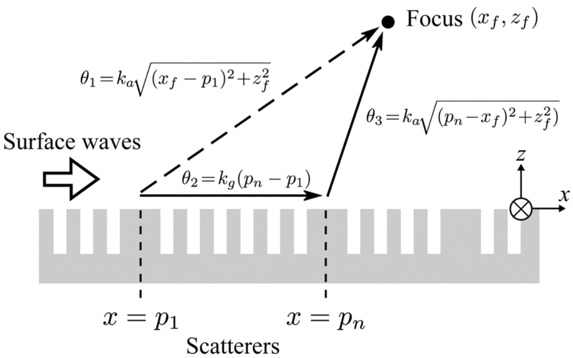

Fig. 3. Principle of focusing based on waveguide scattering. If the phase difference between the solid line and the dotted line equals to a multiple of 2π, the waves interfere constructively, and a focus is generated.

the propagation of the surface waves. Thus, they radiate the surface waves into the air with defined phase delays. Focusing is achieved when the scattered waves interfere constructively at a single point in the air. In this letter, we define the center of the waveguide as the coordinate origin. To generate a focus at (x_f, z_f), nth scatterer position $x = p_n$ is calculated by the following equation (Fig. 3):

$$k_g(p_{n+1} - p_1) + k_a\sqrt{(x_f - p_{n+1})^2 + z_f^2} - k_a\sqrt{(x_f - p_1)^2 + z_f^2} = 2\pi n \quad (1)$$

where k_a and k_g denote wavenumbers in the free space and on the waveguide, respectively.

The surface mode is TM polarized, i.e., the magnetic field holds the y-component only [14]. To excite the waveguide, we develop a coupler shown in Fig. 2, which has originally been employed for dielectric image lines [19]. Two metallic walls are placed on the aluminum plate. A coaxial cable with a lengthened inner conductor is vertically inserted at the center of this coupler. Due to the cutoff effect between the two walls, backward wave propagation is prohibited, and thus the forward propagation is efficiently excited. We determined the length of the inner conductor to be 2.4 mm to minimize the radiation loss directly into free space based on a numerical simulation.

III. EXPERIMENT

Our experimental setup is illustrated in Fig. 4. The chirped grating pattern is designed to generate a focus at $x = 0$ cm, $z = 30$ cm. The focusing antenna and a dipole antenna are connected to ports 1 and 2 of a network analyzer (Agilent

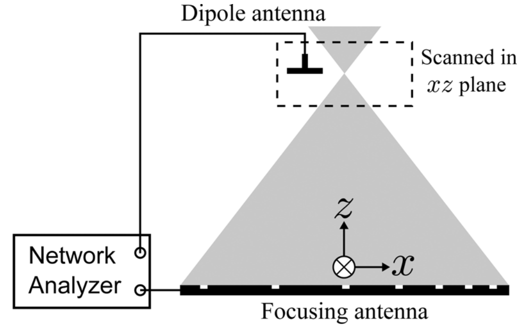

Fig. 4. Experimental setup. A dipole antenna is moved in xz-plane at 2-mm intervals to map the power density distribution.

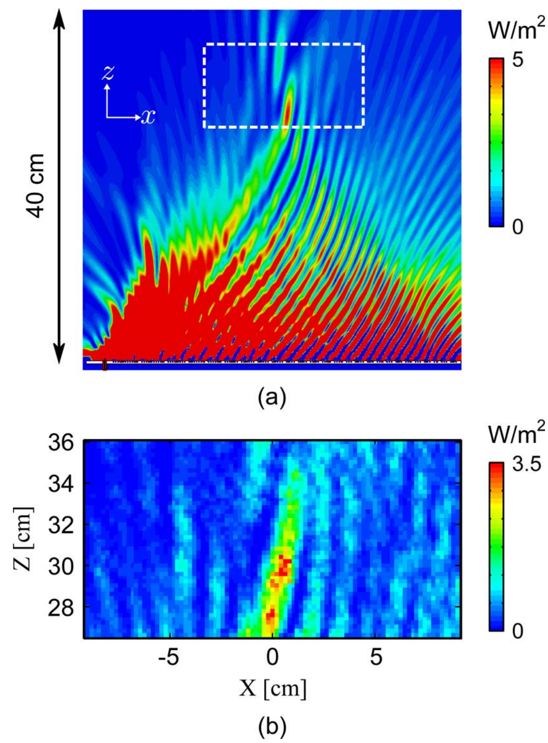

Fig. 5. Power density distribution maps at 20 GHz. (a) Simulation and (b) measurement. The measured area (-9 cm -9 cm $\leq x \leq 9$ cm, $y = 0$ cm, 26.6 cm $\leq z \leq 36$ cm) in which the color bar is valid is indicated by the dashed square in upper figure.

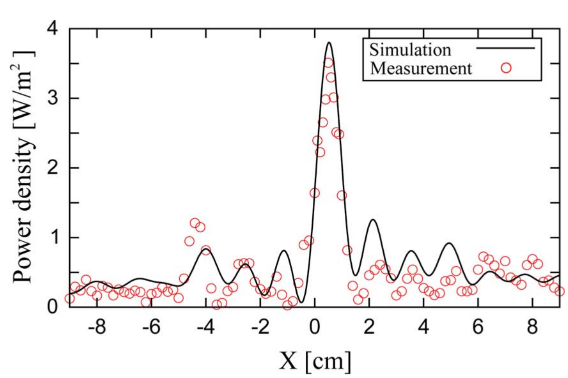

Fig. 6. Profile of the focus at 20 GHz at $z_f = 30$ cm. The full width at half-maximum of the focus is about 9.7 mm, which equals to 0.65λ.

E5071C), respectively. We measure the spatial distribution of S_{21} at 2-mm intervals and convert it into a power density map by the Friis transmission formula assuming the receiver

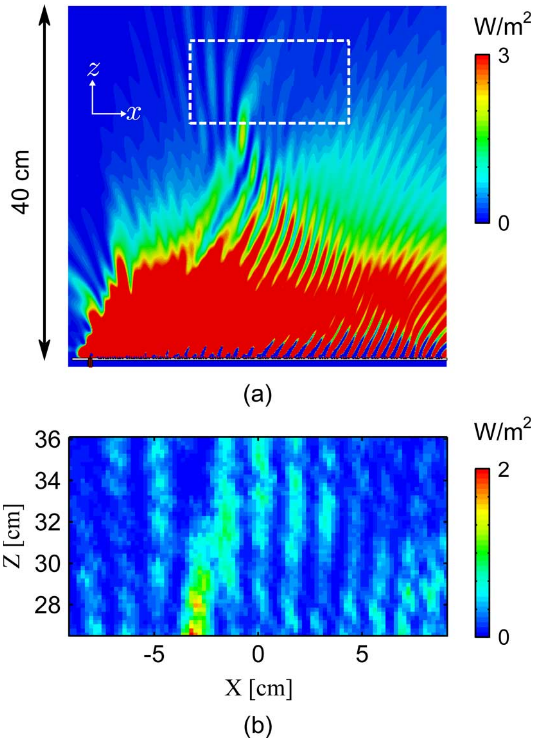

Fig. 7. Power density distribution maps at 18 GHz. (a) Simulation and (b) measurement. The measured area in which the color bar is valid is the same as Fig. 5.

antenna gain of 2.0 dBi. The experimental results are compared to simulations performed by CST MW Studio. We present the experimental results by normalizing the input power to be 1 W in accordance with the simulation.

Fig. 5 compares the power density distribution between (a) simulation and (b) measurement at 20 GHz. The measurement is in good agreement with the simulation, and the focusing effect is clearly observed. The profiles of the power density at $z = 30$ cm is shown in Fig. 6. In this figure, the power density is measured at a 1-mm interval. The full width at half-maximum (FWHM) of the focus is about 9.7 mm, which equals to 0.65 λ. It should be noted that the focus is spreading in the y-direction as the device has no focusing effect in that direction. Due to the dispersive nature of the structure, the focus moves as the frequency changes [20]. It always moves in the negative x-direction as the frequency decreases. This tendency is confirmed in Fig. 7, where the focus appears at $x = -3$ cm at 18 GHz both in the experiment and the simulation.

From the CST simulation, we roughly estimate the power allocation of the system at 20 GHz. Out of the power fed from the coaxial cable, 75% was converted to surface waves, and the other was either emitted to the air as a stray radiation (22%) or reflected back to the coaxial cable (3%). The scatterers radiated 59%, and 16% was transmitted to the end of the waveguide getting converted directly to an endfire radiation owing to a negligible back reflection. Eventually, 15% was focused within the FWHM. The ohmic loss at the conductor was only 0.7%.

IV. Conclusion

We have presented a 20-GHz focusing antenna based on corrugated waveguide scattering. The focusing effect of the device was experimentally demonstrated. We also proposed a coupler to excite the 1-D surface waveguide from a coaxial cable. In this letter, the focal point is fixed because the chirped grating pattern is static. Reconfigurable grating patterns would be realized by incorporating variable components such as p-i-n diodes or field effect transistors (FETs) into the waveguide structure [21], [22]. The tunable structure will implement the steering of focus in this frequency band.

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