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Fabrication of 3D Feed Horn IR Antenna for IR Detector

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Abstract - A three dimensional feed horn 10 μm wavelength infrared antenna has been suggested, fabricated and characterized. It was applied to an infrared detector for efficient collecting of IR radiation and for reducing background noise. The horn antenna size was designed for maximum antenna directivity. The 3D feed horn antenna mold was fabricated using rotating and tilted illumination while the antenna plate was constructed by way of electroplating. Antenna characteristics were measured by coupling with a microbolometer. Measurement results indicated that the directivity of the antenna is 16.1dB and the background noise is reduced by approximately two times.

Keywords: Feed horn antenna, IR detector, IR antenna

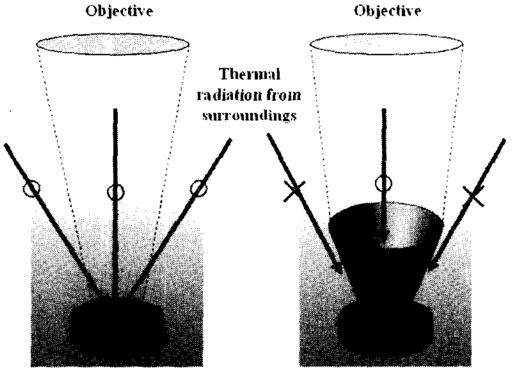
1. Introduction

In the past, applications of antenna to the detector have been focused on the microwave and millimeter wave region. However, nowadays the infrared (IR) type antenna is being applied to the IR detector in a 10 μm wavelength region and related research is being performed by a variety of groups. Various antennas, including dipole, bow-tie and spiral type antennas have been used as the infrared antenna for the IR detector. The above method of coupling the antenna to the IR detector has normally relied on the coupling of two-dimensional antenna with the IR detector [1–4].

The two-dimensional antenna coupling configuration for IR detectors does have certain drawbacks. One such disadvantage is that the coupling of the two-dimensional antenna results in a significant increase in the size of the IR detectors, causing difficulties in array type manufacturing, and resulting in low directivity of the antennas.

On the other hand, the three-dimensional antenna has not yet been applied to the IR detector. Three-dimensional antenna coupling for the IR detector carries a number of advantages. In particular, the feed horn antenna has high directivity and polarization independent characteristics. To explain the advantages of the 3D feed horn antenna, it will be compared with the proposed feed horn antenna coupled IR detector, or the 'open structure' IR detector. The open structure IR detector is sensitive to thermal radiation from all angles that effectively degrade its sensitivity. The feed horn, conversely, has relatively high directionality. The antenna beam produced by the feed horn is restricted to a cone angle of acceptance defined by its aperture size and axial length, and, as a consequence is only sensitive to thermal radiation emanating from the scene to be imaged. Fig. 1 indicates the difference between the open and feed horn coupled detector pictorially. It can be seen from Fig. 1 that the open detector must be shielded or baffled in order to avoid the reception of uncontrolled sources of thermal radiation. However, the baffle must be an absorbing material in order to evade spurious reflections and also be ideally maintained at a constant temperature to reduce system instability. Because the feed horn coupled detector is well coupled to the objective, baffling is far less critical and both sensitivity and stability are significantly improved.

In spite of its positive properties, there is an obstacle in the fabrication process of the 3D feed horn antenna when using the conventional machining method. As a result, an innovative lithography method by the mirror reflected parallel beam illuminator has been used for compact fabrication [5, 6]. In the following section, the design, fabrication and measurement results of this new IR antenna will be presented.



(a) (b)

Fig. 1 Advantage of the antenna coupled IR detector.
(a) all background signals are received but (b) protects against unnecessary noise by the feed horn antenna

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2. Feed horn antenna theory

A variety of feed horn structures have been developed for use in the microwave and millimeter wave region and selection of the most appropriate type is essentially dependent upon application. The antenna pattern directionality (gain) and quality (defined by side lobe content and pattern symmetry) produced by feed are controlled by variation of the aperture size and axial length. Selection of the most suitable feed horn dimensions depends on the application requirements, but it is usually desirable to choose a combination of both aperture size and axial length that maximize antenna directivity and minimize side lobe content. The size of the feed horn aperture will affect the spatial sampling capability of the imager and consequently, should be minimized along with the axial length for fabrication reasons. However, too great a reduction in the aperture size and shortening of the length will degrade the antenna pattern quality, e.g., by increasing side lobe levels, and reducing the imaging capability of the system.

Directivity is the most important factor in the antenna's performance. Therefore, the optimum size of the antenna was designed with excellent directivity at a 10 ㎛ wavelength. The directivity of the antenna is expressed as the following equation (1). [7]

$$D_r(dB) = 10\log_{10}\left[\varepsilon_{ap}\frac{4\pi}{\lambda^2}(\pi a)^2\right] = 10\log_{10}\left(\frac{C}{\lambda}\right)^2 - L(s),$$
$$L(s) = -10\log_{10}(\varepsilon_{ap}) \cong (0.8 - 1.71s + 26.25s^2 - 17.79s^3)$$
$$s = \frac{d_m^{\ 2}}{8\lambda l}, \qquad (1)$$

where a is the radius of the horn at the aperture, $L(s)$ is the directivity loss for aperture efficiency, C is the aperture circumference, d_m is horn diameter, λ is wavelength, l is horn length and s is the maximum phase deviation. Fig. 2 indicates the directivity of the feed horn antenna for various horn lengths as a function of horn diameter using the above equation (1). Optimum horn lines indicate dissimilar horn length, and the horn diameter has been selected in this line considering fabrication feasibility. According to the above result, the directivity of the designed feed horn antenna had 20.4 dB when the diameter of the horn was 54 ㎛ and the height of the horn was 44 ㎛.

It is often convenient to derive simpler expressions, even if they are approximate, to compute the directivity. For antennas with one narrow major lobe and very negligible minor lobes, the beam solid angle is approximately equal to the product of the half power beam widths in two perpendicular planes. For a rotationally symmetric pattern, the half power beam width in any two perpendicular planes are the same. The half power beam width is calculated from the equations (2) and (3). When directivity D=20.4dB, half power beam width θ is 18.5 ° [8]

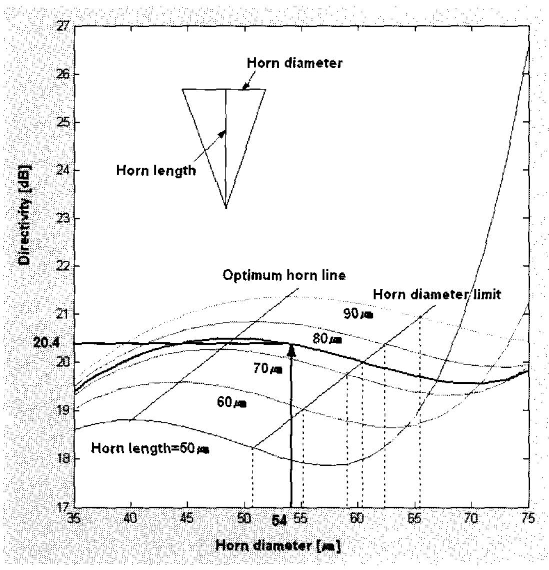

Fig. 2 Directivity of the feed horn antenna for various horn lengths as a function of the horn diameter

$$D_0 = 4\pi/\Omega_A \approx 4\pi/\theta_{1r}\theta_{2r}, \quad \Omega_A \approx \theta_{1r}\theta_{2r}, \quad \theta = \theta_{1r} = \theta_{2r} \qquad (2)$$

$$D_0 \approx 4\pi(180/\pi)^2/\theta_{1d}\theta_{2d} = 41{,}253/\theta_{1d}\theta_{2d} \qquad (3)$$

Where,

Ω_A = beam solid angle

θ_{1r} = half power beam width in one plane (rad)

θ_{1r} = half power beam width in a plane at a right angle to the other (rad)

θ_{1d} = half power beam width in one plane (degrees)

θ_{1d} = half power beam width in a plane at a right angle to the other (degrees)

A quantitative estimate must be determined for the background noise reduction afforded by the use of a feed horn coupled detector compared with the open structure type. In this case we consider Fig. 3 in which a detector is shown at the center of a hemisphere of radiation intensity with the Z direction pointing towards the primary objective. If we define radiation intensity U_m as the power per unit solid angle then the total power received ,W, is given by equation (4);

$$W = \int_0^{2\pi}\int_0^{2/\pi} U_m \sin\theta d\theta d\varphi \qquad (4)$$

Radiation within angle ω is considered to have an intensity of U_1 whereas radiation greater than ω has an intensity of U_2. Considering first the open structure detector, this device is sensitive to radiation occurrence from all angles of the hemisphere and from this equation we may write that the total received power, *Wo*, is given by equation (5);

$$W_o = \int_0^{2\pi} \int_0^{\omega} U_1 \sin\theta d\theta d\varphi + \int_0^{2\pi} \int_{\omega}^{\pi/2} U_2 \sin\theta d\theta d\varphi \tag{5}$$

Now considering the feed horn coupled detector, this device is primarily sensitive to radiation from the objective reception angle ω. Hence, we may write the total received power for the feed horn coupled detector as equation (6);

$$W_a = \int_0^{2\pi} \int_0^{\omega} U_1 \sin\theta d\theta d\varphi \tag{6}$$

Forming a ratio of received powers for the two structures we have equation (7);

$$\frac{W_o}{W_a} = 1 + \frac{\int_0^{2\pi} \int_{\omega}^{\pi/2} U_2 \sin\theta d\theta d\varphi}{\int_0^{2\pi} \int_0^{\omega} U_1 \sin\theta d\theta d\varphi} \tag{7}$$

From this equation, we can see that the additional radiation power entering the open structure detector is U_2 and since this power does not emanate from the scene it can be considered to be a source of noise. For example, if U_2 is small (this could be arranged by cooling the baffle) then $W_o/W_a=1$ and both detectors have identical coupling performance. If the scene temperature is low or U_2 is high, then the ratio W_o/W_a becomes large and the open structure detector become noise dominated with the feed horn coupled device.

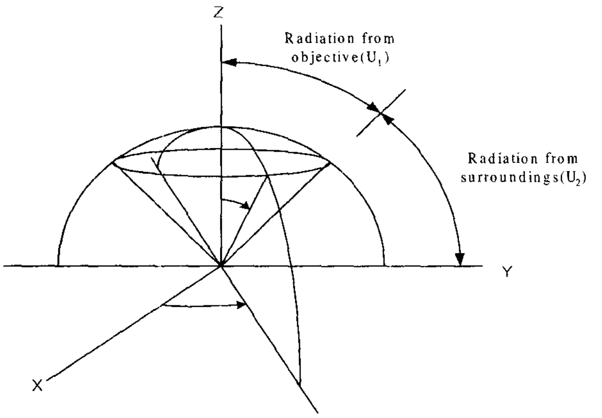

Fig. 3 Spherical coordinates for a point source of radiation in free space.

3. Fabrications

Fabrications of 3D feed horn antennas were carried out using the Mirror Reflected Parallel Beam Illuminator (MRPBI) system, which can rotate and tilt the stage and has a very parallel beam illumination. The 3D feed horn shape mold was acquired through this lithography method. Fig. 4 illustrates a SEM picture of the horn shape mold of the antenna. An antenna plate was fabricated from the antenna mold using an electroplating method (Fig. 5). First, the Cr/Au seed layer for electroplating was patterned. Then the PMER NCA3000 (negative photoresistor) for the antenna mold was fabricated. Next, Ni electroplating was performed on the mold, and the photoresistor (PR) remover was used to remove the mold. Finally, the seed layer was wet etched, and the antenna plate was released. Fig. 6 provides a SEM image of the released antenna plate.

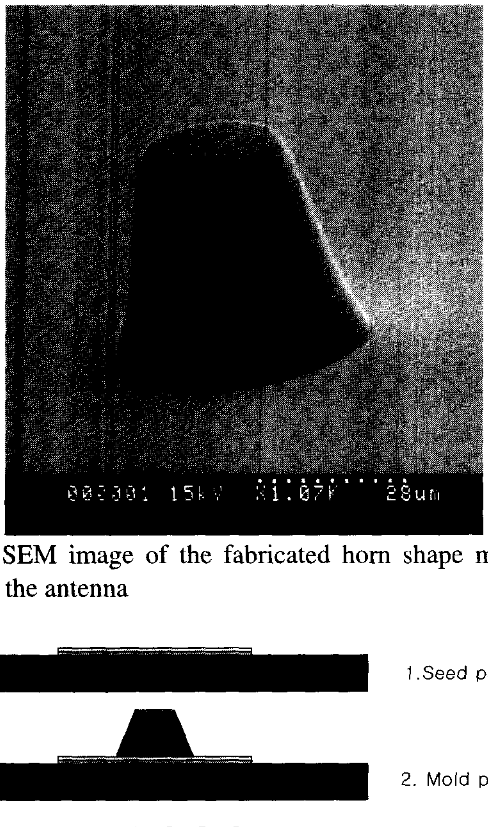

Fig. 4 SEM image of the fabricated horn shape mold of the antenna

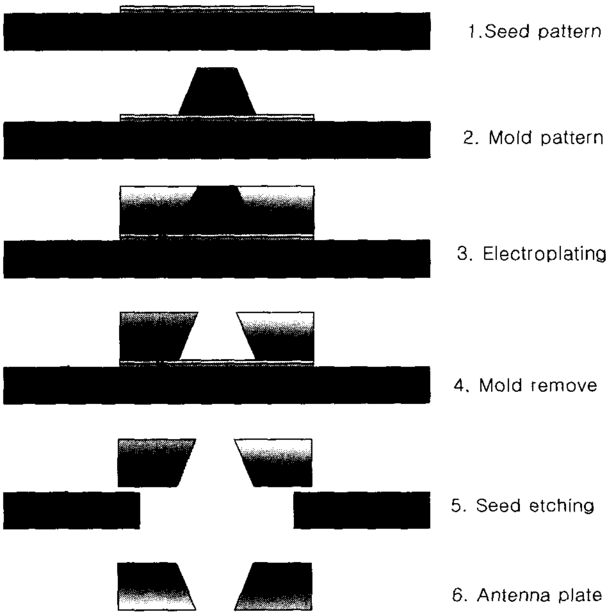

Fig. 5 Fabrication process of the antenna plate

Once fabrication of the antenna was completed, it had to be assembled with the IR detector to measure antenna characteristics. This was because the bonding gap between the IR detector and the antenna was so small that the conventional bonding method was not applicable [9]. The polydimethylsiloxane (PDMS) injection bonding method was therefore used [10, 11]. First, a microchannel was constructed. Next, PDMS was injected to the microchannel as a bonding material. The PDMS acted as a bond between the IR detector and the antenna. Fig. 7 gives a SEM image of the final antenna-coupled IR detector using the PDMS injection bonding method.

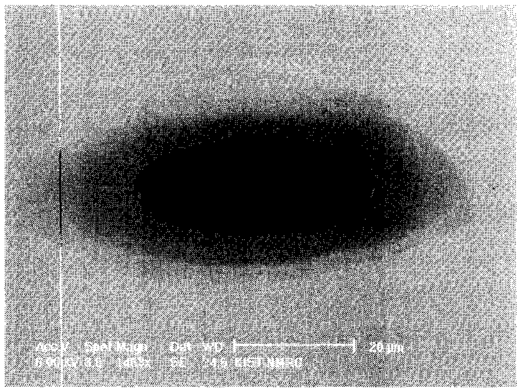

Fig. 6 SEM image of the released antenna plate.

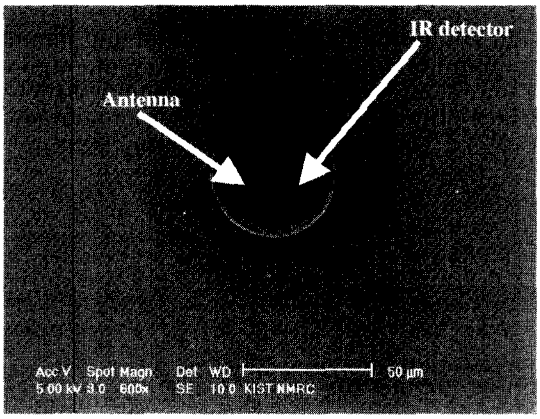

Fig. 7 SEM image of the final antenna coupled IR detector using the PDMS injection bonding method.

4. Results and discussions

Measurement of antenna characteristics can be divided into two aspects, directivity and background noise reduction.

Within the millimeter and submillimeter wavelength range, the conventional method of feed horn antenna pattern measurement involves combining the feed horn with a coherent source and illuminating a suitable detector placed in the far-field, or vice versa. Either the feed horn or detector is rotated about the antenna phase center and the radiation intensity is measured at different off-axis angles. A similar antenna measurement technique can be used within the infrared wavelength range. However, although it is necessary to integrate a detector with the antenna, it will prove simpler to modify the measurement scheme. The CO_2 laser produced 10.6 μm infrared radiation. The laser source was modulated by optical chopper. The antenna coupled IR detector loaded on the rotation stage had a directional change from 0° to 50°. Then the signal voltage was measured as a function of the direction angle. Measurement results demonstrated that when the antenna direction angle was about 10° the signal fell rapidly and after 50° the signal was not reduced anymore. Fig. 8 shows a comparison of the signal output of the antenna coupled IR detector and the signal of the open structure detector. From the above figure, the open structure detector does not reduce the signal as to the direction angle, that is, it has very low directivity. However, the antenna coupled detector rapidly reduced the signal. From the graph, the antenna's half power beam width shows 32° and using equation (3), the antenna's directivity was calculated on 16.1dB.

This result is somewhat different from the simulation result. It comes from the fact that fabricated antenna size (horn diameter is 50μm) is slightly different from the designed antenna size (horn diameter is 54μm) because of fabrication tolerance. Furthermore, the surface of the horn antenna is not ideal. It leads to interference between lights from the horn surface. However, this value has higher directivity than that of the two dimensional antenna.

It was measured as to how much the background noise is reduced. Fig. 9 gives the noise comparison graph before antenna coupling and after antenna coupling as a function of chopper frequency. The background noise reduction appeared on the antenna-coupled detector about two times more than on the open structure detector. We can infer that from equation 7 the background noise U_2 is high. It can be seen that the antenna's directivity characteristics cut off the unnecessary background noise.

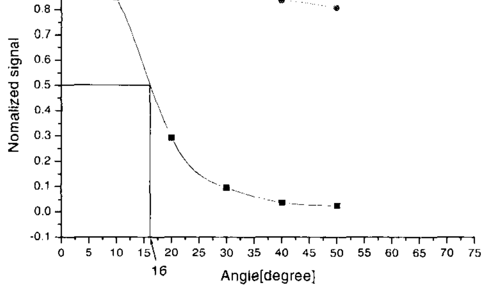

Fig. 8 Comparison of directivity between antenna coupled device and open structure device

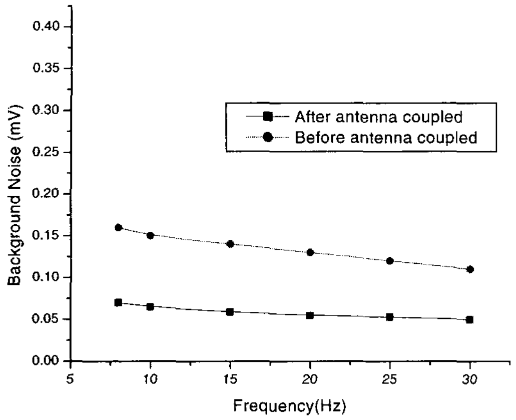

Fig. 9 Comparison of background noise signal between antenna coupled device and open structure device

5. Conclusions

In this paper, a 3-dimensional feed horn infrared antenna was designed, fabricated and characterized. The 3D feed horn antenna was constructed by a tilted and rotation lithography method. Antenna's performances were characterized by measuring directivity and noise signal. It had superior directivity (16.1dB) over the 2D antenna. It also cut off the unnecessary background noise effectively. The characterization of the feed horn antenna confirmed that this antenna can enhance performance of the IR detector.

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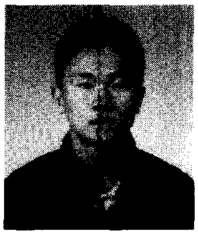

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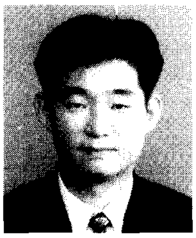

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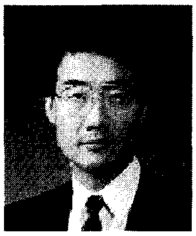

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