Development of Film Lens Antennas for Large Aperture Radio Telescopes

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ABSTRACT

There are various ways to achieve high sensitivity of radio telescopes. Conventional reflectors have problems in enlargement of aperture size because it is difficult to keep accurate reflector surface. While the operational frequency becomes higher, or the aperture becomes larger, the distortion normalized by operational wavelength becomes larger. However, lens is not sensitive to these errors, no studies have ever done to use for radio telescopes, because lens is lossy and heavy. Film Lens Antenna(FLA) is a fundamentally unique lens using phase shifters and light weight. 90-cm FLA for 22GHz was made and measured its efficiency.

INTRODUCTION

There are various studies or projects to construct more sensitive radio telescopes toward far, faint, small objects in the universe which we have never observed, for examples, ALMA, SKA, GALAXY, VERA, etc. Film Lens Antenna(FLA) is a novel lens antenna to build large aperture.

The sensitivity of single dish of a parabolic antenna for continuum observations is given by

$$\left(\frac{S}{N}\right) \propto \frac{A\eta S\sqrt{\Delta B \Delta t}}{T_{sys}} \tag{1}$$

$S$is the flux density received from the source in the universe. The aperture area is A and its aperture efficiency is η. In the case of the interferometer, we use correlate flux $\sqrt{A_i\eta_i A_k\eta_k}S$ instead of $A\eta S$ in the single dish. i, k is for the number of the element antenna of the interferometer. T_{sys} is the system noise power also by temperature containing all noises added to the signal.

VLBI(Very Long Baseline Interferometer) is used to obtain high spatial resolution, because the spatial resolution of the telescopes is proportional to $\frac{D}{\lambda}$. D is the aperture size in single dish observation, however it is the maximum baseline length of two element antennas in the interferometer. λ is the operational wavelength, thus, observing in higher frequency may be another way to fine resolution, however astronomers have interest in physical structures and processes in the source objects which varies in frequency. Nowadays we can use Space VLBI technique which is a interferometer composed of element antennas on the earth and on the Japanese artificial satellite which is launched in 1997 for VLBI and named ‘HALCA‘. ‘HALCA‘ has a main reflector of 8-meter diameter which is a parabolic reflector antenna and made by deployable mesh newly developed for this mission to be light weight and able to collect waves up to 22GHz. While the antenna of ‘HALCA‘ is small, its maximum baseline in current Space-VLBI is up to $3.0 \times 10^5 km$ which has never been reached before on the ground.

There are various ways to achieve high sensitivity by Eqs. 1. VERA uses 2-beam antennas for differential VLBI which reduces phase error of the source signals caused by the atmosphere fluctuation to elongate $\Delta t[sec]$. GALAXY uses wide-band optical fiber network to transportation of the digital data received by antennas. The bandwidth will be over 10GHz in their near future plan by WDM(wavelength division multiplexing). SKA is a plan of an array on the earth with large aperture size of square kilometers. Reducing the noise has the quantum limit in the nature. Enlargement of the aperture size has no limit but the technical reason. The Author’s concern in this paper is to realize a new method to construct large collecting area for radio telescopes for the future astronomy.

FILM LENS ANTENNA

Conventional reflectors have problems in enlargement of aperture size because it is difficult to accurate reflector surface. While the operational frequency becomes higher, or the aperture becomes larger, the distortion normalized by operational wavelength becomes larger. The magnitude of the distortion is changing with the direction of the telescope, with the wind velocity, even more with the temperature distribution depend on the declination of the sun.

In the space, the antenna is not distorted by the gravity and wind load, however the temperature difference between the sunny and shadow side will reach several hundreds of Kelvin which is ten times larger than in the atmosphere. The weight of the antenna itself is also a problem when we launch it into the space because the payload is limited by the launch vehicle. Therefore, a deployable parabolic mesh antenna was developed for the main reflector of "HALCA". This reflector is made up wire meshes to be light weight and kept its paraboloid surface with controlled tension on the wires. While it is light mass of 200Kg including back structure, its aperture size is merely 8m. Tension on wires were set carefully before launch. That antenna can be operational up to 22GHz which is limited by its surface accuracy.

By Huygens-Fresnel's principle, the surface deviated from accurate paraboloid causes phase error in the wave reached at the focus. In the case of lens, surface deviation by distortion is almost cancel out on its two surfaces. This is advantageous over the reflector. It should be noted the total phase error is determined by the $differential$ of each surface error.

In the case of the inclination error of lens material body, it is almost cancel out by error of the first surface (air to dielectrics) and the second (dielectrics to air). By the comparison the reflector to the lens, the performance of the reflector is more sensitive to its surface accuracy than the lens. Lenses are more indulgent also to the surface inclination errors than reflectors.

However, no studies have ever tried to use a lens as the primary collecting device of a radio telescope. For this purpose, the aperture diameter of lens becomes as large as several meters or above, however it needs homogeneous and transparent materials over the aperture. Moreover insertion loss and the reflections by impedance mismatching at the surface are the problems in using lenses. R.Milne made a lens with artificial dielectrics which is shorted dipole stacks of seven layers [3]. The efficiency of that lens was measured 40 percent, however it is complex and heavy for telescopes. As a result, the parabolic reflector has been used as a main reflector because of simple structure and low losses.

Y. Chikada, mentioned a kind of the Fresnel zone plate lens antenna with positive and negative phase shifter arrays on the surface which reduce the phase error and improve aperture efficiency, The lens is consisted of the flexible thin films with printed circuit and it would be very light and also be deployable to be suitable for satellite application like 'HALCA', or the future space radio telescope with a gigantic aperture over $1km$ [4]. Y.Chikada and S.Toyomasu calculated the efficiency of a lens with single surface of phase shifter arrays which lens was assumed to be consisted of coaxial zones with periodically placed four different phase-shift steps. On its surface, long and short dipoles are placed to make negative and positive phase shift respectively they are placed between a perfect transparent zone with no phase shifter and next perfectly opaque zone to make a gradient of the phase shift along lens radius. The opaque zone is placed for the phase shift of π, the null zone for 0. Because, phase shifters made by single resonance circuit can not have transparency at its resonance frequency where its phase shift reaches $\pi/2$. The aperture efficiency of this lens was calculated nearly 20 percent which is merely the twice of the Fresnel zone plate lens which has perfect transparent zones and opaque zones only. They considered this lens has very narrow relative bandwidth about 1 percent [5] due to the resonance characteristics of phase shifter circuit, however it would receive larger power from radio sources than other conventional reflectors ever made. Because their lens could made to be very light weight and the huge aperture diameter of 1 km, which has been never made, would be capable to be launched into the space.

However the weight is light, we must pay attentions to the efficiency because this lens is a kind of the Fresnel lens. Large aperture has large Fresnel index, thus large Fresnel lenses have narrow bandwidth. If the transparency of lens, the efficiency is worse, we need excess diameter to receive same power compared to the reflector antennas. But this excess diameter leads the large Fresnel index to reduce bandwidth and also it would be heavier. Also it is to be noted that their consideration about narrow bandwidth is wrong. Because the phase shifter is used from resonance frequency to have certain transparency, transparency and phase shift changes more slowly to the frequency than near resonance where transparency 0 and phase shift is $\pm\frac{\pi}{2}$. Also, phase error is estimated to be under $\pm\frac{\pi}{4}$, because the phase shifters is not used for the zones for which phase shift is near 0 and π. Even though interference between reflected waves and transmitted wave in two or more phase shifter surface can make π phase shift with transparency of the total films by careful control of separation of films, these configuration is sensitive to the error in film separation and to the wavelength, in other words, to the frequency. Therefore, other configuration was to be established to realize thin film efficient lens antenna.

The Author H.UJIHARA improved the efficiency of such film lens antenna by using two or three phase shifter films with narrower spacing than the wavelength to enhance the effect of the mutual coupling of phase shifter films. The component of the current on the phase shifters induced by the mutual coupling becomes stronger with approaching surfaces to each other. Finally it is considered the characteristics of transparency changes from isolated condition to be transparent with phase shift near π over several percents in relative bandwidth and more slowly changes with frequency than previous configuration of single film or films using interference. This, A novel kind of lens antennas, was named Film Lens Antenna (FLA).

EXPERIMENTAL RESULTS AND DISCUSSION

A numerical scheme developed by James. P. Mongomery [2] can handle one dielectric layer and conductor surface on the Moment Method and periodical boundaries. However, FLA uses more layers of dielectrics and conductors, thus a numerical scheme was extended was developed and numerical code was written to simulate the characteristics of FLA films by the Author H.UJIHARA. As a result of this simulation with this code, it was confirmed FLA film is transparent with phase shift near π under the condition of two or three films distanced from each other around $\frac{1}{4}$ wavelength and these characteristics is controlled by design parameters of the phase shifters and film separation [6]. Based on this result, experimental films were made and measured their characteristics. Parameters for the edge effect of the conductors in this code is calibrated by measurement for single film configuration. The characteristics of two film configuration were measured with changing the separation of films from 0.4 wavelength to 0.1 wavelength. The result was agreed with simulations. Measurement errors are considered to be due to random miss-alignment of the film in long separation and randomness of the surface in close distance because the tension on the films is not enough siteLaLa2. The error in this experiment is at most 10 percent in amplitude and 25 degree in angle[8], and thus it is concluded that the measurement does not contradict numerical simulation Therefore the numerical scheme can be used for design the phase shifters of FLA.

According to these results, FLA is designed as Fig.1. dz is film separation. W is conductor width which is normally thin compared its length. L is length of shorted cross dipole in this figure. Instead of dipoles, loops are usable to be dense array. This is a kind of Fresnel lens, so it is operational for higher harmonic bands without break its Fresnel zoning structure for lower bands when corresponding phase shifters are placed on the surface. Efficiency of this lens is estimated around 50 percent or over with three film configuration which has a zone of nearly π phase shift, or around 40 percent with more simple configuration which has two shorted dipole patterns same on each two films[8].

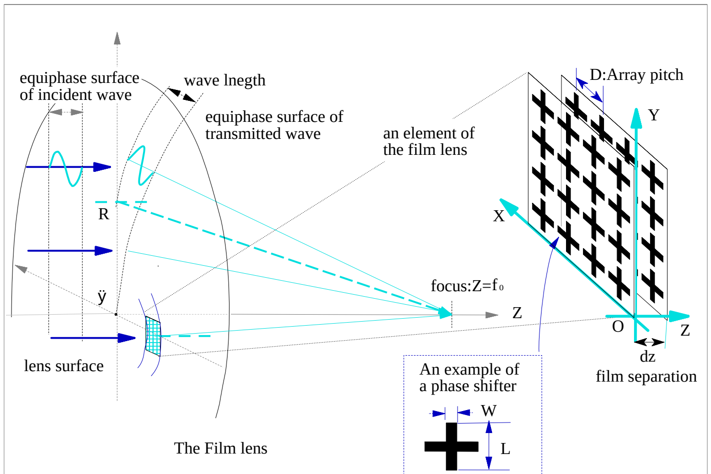

Figure 1: Configuration of Film Lens Antenna.

90-cm experimental lens for 22GHz with focal length of 1.82m was made by the later design in 2001. Its efficiency was measured and compared with single film configuration and Fresnel zone plate lens by receiving with crossing the Sun in the beam of the fixed lens. Beam pattern of FLA is shown by red and its of single film is green in Fig.2 and surface is shown in Fig.3. The efficiency of these lenses is agreed with estimation, therefore architecture of FLA is established.

CONCLUSION

In this present work, the concept of FLA for radio telescopes was introduced, numerical scheme to study FLA was developed, and characteristics and composition of the phase shifter films for FLA are discussed physically and numerically examined, and finally measured by experimental films and lens. Dipole array surface is used in flat reflectors, or, polarization or frequency selective surface, but it has not ever used for the lens except in making artificial dielectrics by R.Milne.

FLA introduced in this paper is a fundamentally unique structure in the point that the composition of phase shifter films which works as one phase shifter film in the separation where the mutual coupling is not negligible to enhance the transparency and phase shift both, which does not work as artificial dielectrics. It is concluded that the efficient and practical FLA for the large aperture telescopes by numerical and experimental.

It should be also mentioned on FLA. The radio telescope on an artificial satellite is required to be light weight, and deployable. Shaping plane of FLA at orbit is quite easier than parabolic surface. While 'HALCA' with a reflector antenna is operated up to 22GHz, FLA can be operated more higher for an example 86GHz. Also FLA can make focus even if the lens surface is distorted vertically. The reason is a fact that it is a kind of diffraction lens by phase shifters, thus its surface

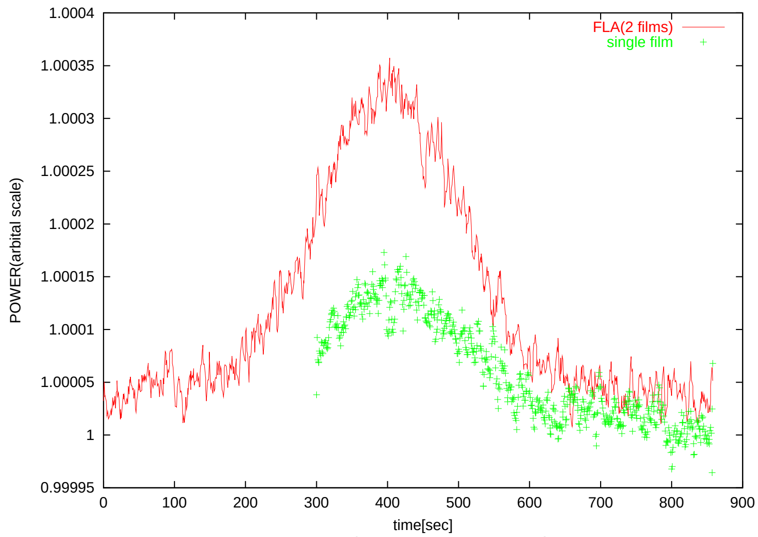

Figure 2: Beam patterns of FLA and single film lens.

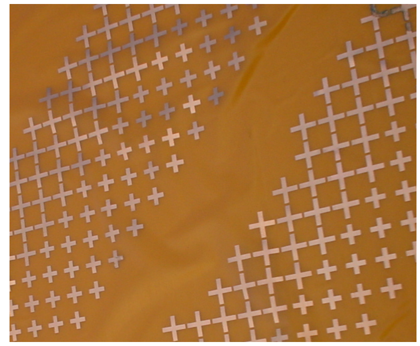
Figure 3: Surface of FLA film

shape and the phase shift of transmitted waves through lens surface are almost independent matters. Moreover, we can design arbitrary shape of lens by properly placed arrays of phase shifter circuits on the lens surface.

Moreover, we can avoid the blockage of main reflector by using lens for the replacement of parabolic reflector. The blockage causes loss of received power and reduce the efficiency by several percents. While an off-set parabolic reflector avoid the blockage, the symmetry for the inertia of the satellite becomes worse and thus the characteristics for the polarization would be rather worse than the symmetrical center-parabola reflector or lens. Thus it is concluded the FLA is useful for these application.

However the receiving system to compensate the chromatics aberration of FLA have not studied. It is important to study the characteristics of large Fresnel index FLA for this aberration to use FLA in large radio telescopes. Receiving system or compensation optics are remained as future works.

References

[1] “Antenna Engineering Handbook”,IEICE, 1980

[2] James. P. Mongomery, ”Scattering by an infinite periodic array of thin conductors on a dielectric sheet”, IEEE Trans. AP-23, pp. 70-75. Jan. 1975

[3] R.Milne, ”Dipole Array Lens Antenna”, IEEE Trans. AP-30,No. 4, pp.704-712,1982

[4] Yoshihiro CHIKADA, ” Millimeter wave gigantic radio telescope by lens antenna ”, ISAP, Proc. pp. 959-962, 1985

[5] Sinji TOYOMASU ” A first step for development of radio telescopes of next generation”, Master Thesis, Toyohashi University of Technology, 1994.

[6] Hideki UJIHARA, Yoshihiro CHIKADA, ”Lens antennas for a radio telescope”, IEICE journal, Vol.J81-B-II No.12 pp.1145-1148, Dec. 1998.(in Japanese)

[7] Hideki UJIHARA, Yoshihiro CHIKADA, Katsuko NAKAHIRA ”Measurement of film lens elements for large radio telescopes”, IEICE journal, Vol.J84-B,No.2,pp.295-302,Feb. 2001. (in Japanese)

[8] Hideki UJIHARA ”Measurement of film lens elements for large radio telescopes” unpublished, Thesis for Ph.D. , Graduated University of Advanced Studies, 2001.

[9] Hideki UJIHARA, Yoshihiro CHIKADA, Katsuko NAKAHIRA ”Aperture efficiency of 90-cm film lens antennas”,unpublished,