Film Lens Antennas for Large Aperture Space Radio Telescopes

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INTRODUCTION

Antennas most commonly used in radio telescopes are parabolic reflector antennas. To improve angular resolution of the radio telescopes, VLBI(Very Large Baseline Interferometer) is used. Also Space-VLBI is used, which is composed of the satellite " HALCA " with an 8-m-diameter antenna and antennas on the earth. Enlargement of aperture size of antennas is a way to achieve more sensitivity for faint cosmic sources.

However, conventional reflectors are sensitive to the surface error caused by the gravitational or thermal distortion.

The situation is not better in the space than on the earth. 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.

It becomes more difficult to keep accurate reflector surface in shorter wavelength or larger aperture. However lens is insensitive to these errors, no studies have ever done to use to make primary focus of radio telescopes, because usual lens has insertion loss and is heavy. Film Lens Antenna(FLA) developed by the Authors is a fundamentally unique lens which uses simple phase shifters on plane films to be light weight, efficient, cost effective and easy deployable.

FILM LENS ANTENNA

By Huygens-Fresnel's principle, the surface deviation 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). Lenses are more insensitive also to the surface inclination errors than reflectors. It is concluded by the comparison the reflector to the lens, the performance of the reflector is more sensitive to its surface accuracy than the lens.

The parabolic reflector has been used as a main reflector, because of simple structure and low loss. For the radio telescopes, the aperture diameter is more than several meters, however usual lens 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. Dipole array surface is also 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.

Y. Chikada, mentioned a kind of the Fresnel zone plate lens antenna with positive and negative phase shifter arrays on the aperture to reduce the phase error and improve aperture efficiency. This lens is proposed to be consisted of the flexible thin films with printed circuit which would be very light and also 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 estimated the efficiency of a lens with single surface of phase shifter arrays which was assumed to be consisted of coaxial zones with periodically placed four different phase-shift steps along radial direction. Long and short dipoles on the film 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

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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 be made very light weight, the huge aperture diameter of 1 km would be capable to be launched into the space.

However the weight is light, the efficiency should be improved. 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 this caused excess diameter to receive same power compared to the reflector antennas. Also worse, this excess diameter leads the large Fresnel index to reduce bandwidth and it would be heavier. However, it is to be noted that their consideration about narrow bandwidth is wrong. Because the phase shifter is used away from resonance frequency to have certain transparency, transparency and phase shift are more insensitive 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 are not used for the zones where phase shift should be near 0 and π. Phase shifter for π needed for efficient lens.

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 would be sensitive to the error in film separation and to the wavelength, in other words, to the frequency.

The Author H.UJIHARA improved the efficiency of this film lens antenna by using two or three phase shifter films with narrower spacing than the wavelength to enhance the 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. It is considered the characteristics of transparency changes from isolated situation and transparency is obtained with phase shift near π over several percents in relative bandwidth and hey would be more insensitive to frequency changes than previous configuration of single film or films using interference. This, A novel kind of lens antennas, was named Film Lens Antenna (FLA) by the Author.

EXPERIMENTAL RESULTS AND DISCUSSION

A numerical scheme developed by James. P. Mongomery [2] can handle one dielectric layer and conductor surface, which is based on the Moment Method and used in periodical boundaries. However, FLA uses more layers of dielectrics and conductors, thus this numerical scheme was extended to simulate the characteristics of FLA films by the Author H.UJIHARA. As a result of this simulation with this code, it was confirmed that FLA film is transparent with phase shift near π with the composition of two or three films distanced from each other around $\frac{1}{4}$ wavelength, and that 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 in this code for the edge effect is calibrated by measurement of 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 to randomness of the surface in close distance because the tension on the films is not enough siteLaLa2. The error in this measurement is estimated at most 10 percent in amplitude and 25 degree in phase [8], and thus it is concluded that the measurement does not contradict numerical simulation. Therefore this numerical scheme is useful to design the phase shifters of FLA.

According to these results, experimental FLAs are 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. Efficiency of this lens is estimated to reach 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 with two films[8].

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

CONCLUSION

The concept of FLA for radio telescopes was introduced, numerical scheme to design FLA was developed, and characteristics and composition of the phase shifter films for FLA are discussed physically and examined numerically, and finally measured by experimental films and lens.

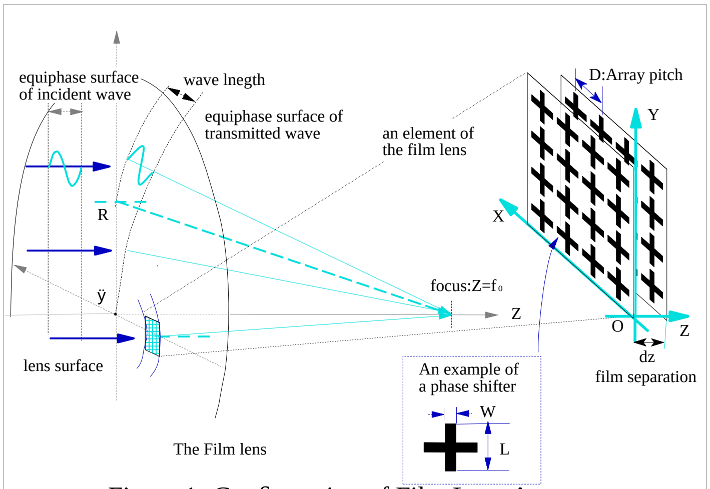

Figure 1: Configuration of Film Lens Antenna.

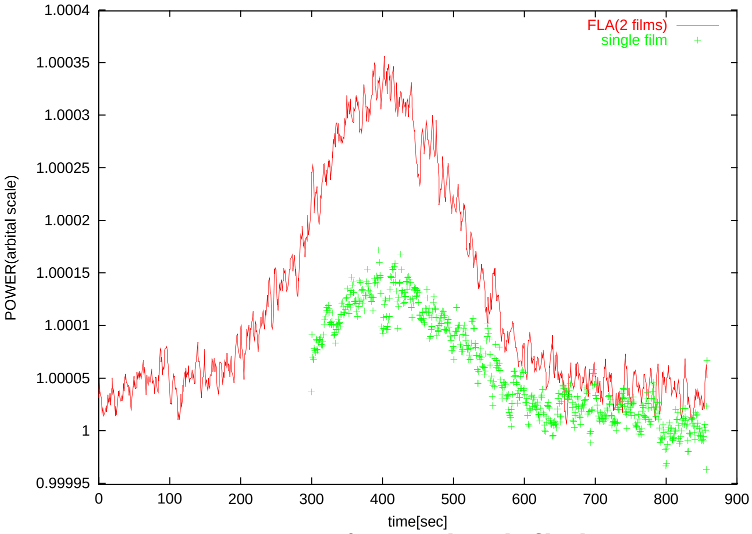

Figure 2: Beam patterns of FLA and single film lens.

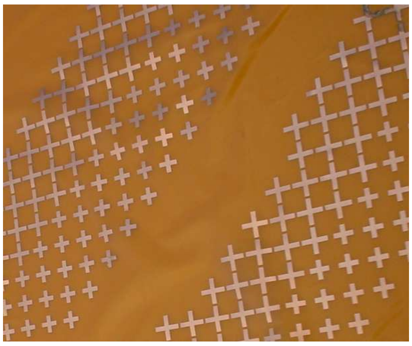

Figure 3: Surface of FLA film

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, which is placed 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 noted FLA is a kind of Fresnel lens, so it is operational for higher harmonic bands with keeping its Fresnel zoning structure when corresponding phase shifters are placed on the surface. Thus it is usable for radio astronomical satellite, for an example 22GHz, 43GHz,and 86GHz corresponding H_2O, O_2, SiO maser lines.

It should be also mentioned on FLA. The radio telescope on an artificial satellite is required to be light weight, and deployable. Shaping mere plane of FLA at the 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 makes the focus by diffraction lens caused by phase shifters, thus the phase shift of transmitted waves through lens surface are almost insensitive to its surface shape. Moreover, we can design arbitrary shape of lens by properly placed arrays of phase shifter circuits on the lens surface.

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 can avoid the blockage, the symmetry in the inertia of the satellite becomes worse and thus the characteristics of the polarization would be rather worse than center-parabola reflectors or lens. Thus it is concluded the FLA is useful for these satellite 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.

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