A Concept of Adaptive Focusing using a Rotman Lens for Detecting Buried Structures

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Abstract

A new concept of adaptive focusing, using a Rotman lens, is presented in this paper. A Rotman lens is a microwave lens which is able to focus microwave power on its focal arc or generate multiple beams. By adding the array of phase shifters between a Rotman lens and antenna elements, the wavefront can be adaptively modulated to focus objects distributed in short range rather than far-field zone. From the optical point of view, the propagations of the lens have been simplified from the Fresnel diffraction integral to the Fourier transform. Using Fourier Transform, a beam propagation method has been developed to show improvement of the resolution by controlling wavefront of wave propagating from an aperture-type antenna array. The beam width(or spot size) and intensity have been calculated for a focused beam propagating from an array having 10λ of its size. For the beam with 20λ, 30λ, and 50λ of geometrical focal length, the half-power beamwidth (spot size) is about 1.1λ, 1.3λ, and 1.9λ, respectively.

Key Word : Adaptive focusing, Rotman Lens, Beam propagation method

I. INTRODUCTION

A radar system processes the received signals scatted from targets according to a spatial signal processing algorithm such as LMS(Least Mean Square) [1]. The spatial signal processing technology is also used in a smart antenna system to synthesize its beam patterns for increasing the ratio of signal to interference(S/I) [2]. The resolution of a radar system is varying with not only antenna size but spatial signal processing algorithm. For near-field detecting applications, it is necessary to adaptively control wavefront to increase the resolution. Spatial pre-filtering is useful in reducing the cost and difficulty of implementing adaptive array systems.

Invented in 1963 by W. Rotman and R. F. Turner, the Rotman lens has been intensively researched for radar applications to its simple design and broadband characteristics [3, 4]. By adding the array of voltage-tunable phase shifters between a Rotman lens and an antenna array, the wavefront can be adaptively controlled according to the distance from an antenna array to a target in order to increase the resolution. In other words, converging circular wavefront having a geometrical focal length can be shaped by adjusting the phase of wave at each radiating element. As a result, the image of targets can be focused on the focal arc of a Rotman lens. For example, shallowly buried mines can be detected in an efficient way. From the theory of Fourier optics [5], a beam propagation method has been developed to show improvement of the resolution for compact mine detection radar.

II. FRESNEL INTEGRAL AND FOURIER TRANSFORM

According to the theory of Fourier optics more specifically the Fresnel diffraction integral in Eq. (1), the wave propagation from an aperture can be expressed as

$$U(x,y)=\frac{e^{jkz}}{j\lambda z}e^{j\frac{k}{2z}(x^2+y^2)}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\{u(\xi,\eta)e^{j\frac{k}{2z}(\xi^2+\eta^2)}\}e^{-j\frac{2\pi}{\lambda z}(x\xi+y\eta)}d\xi d\eta \quad (1)$$

A form of Eq. (1) is recognized to be the Fourier transform of the product of the complex field ($u(\xi,\eta)$) just after the aperture and a quadratic phase factor ($e^{j\frac{k}{2z}(\xi^2+\eta^2)}$). For a two-dimensional scanning Rotman lens, this two-dimensional equation can be simplified to a one-dimensional expression by eliminating variables y and η.

$$U(x)=\frac{e^{jkz}}{j\lambda z}e^{j\frac{k}{2z}x^2}\int_{-\infty}^{\infty}\{u(\xi)e^{j\frac{k}{2z}\xi^2}\}e^{-j\frac{2\pi}{\lambda z}x\xi}d\xi \quad (2)$$

When an aperture is coupled with a lens, the Fourier transform pair is realized between the field distribution in front of a lens and the distribution on focal plane (z=f) as shown in Fig. 1 (a). The quadratic phase factor inside the Fresnel integral is canceled out by the phase function of the lens ($e^{-j\frac{k}{2f}\xi^2}$) at focal plane. The resultant form has the Fourier transform of the field distribution in front of a lens, $u(\xi)$.

$$U_{fp}(x)=\frac{e^{jkf}}{j\lambda f}e^{j\frac{k}{2f}x^2}\int_{-\infty}^{\infty}\{u(\xi)e^{j\frac{k}{2f}\xi^2}e^{-j\frac{k}{2f}\xi^2}\}e^{-j\frac{2\pi}{\lambda f}x\xi}d\xi \quad (3)$$

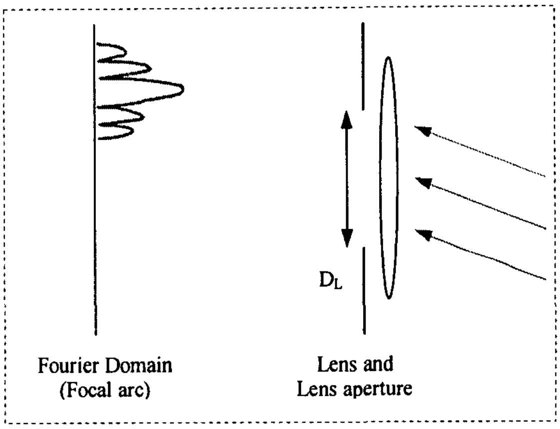
$$=\frac{e^{jkf}}{j\lambda f}e^{j\frac{k}{2f}x^2}\int_{-\infty}^{\infty}u(\xi)e^{-j\frac{2\pi}{\lambda f}x\xi}d\xi \quad (4)$$

Another Fourier transform pair can be observed between the field distribution at an aperture and the distribution at far-field region (Fraunhofer region, $z > 2D^2/\lambda$) as shown in Fig. 1 (b). The quadratic phase factor ($e^{j\frac{k}{2z}\xi^2}$) inside the Fresnel integral is converging to unity as the distance (z) from the aperture increases.

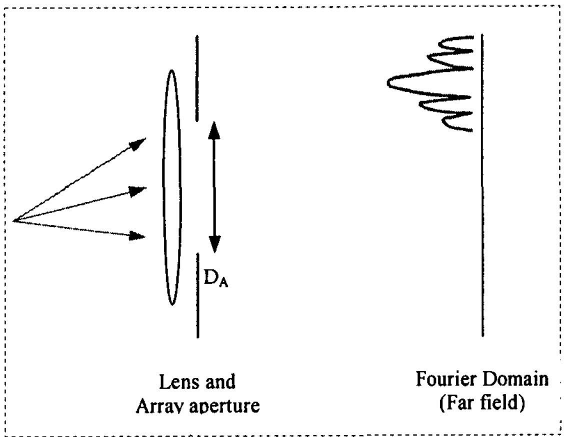
$$U_{ff}(x)=\frac{e^{jkz}}{j\lambda z}e^{j\frac{k}{2z}x^2}\int_{-\infty}^{\infty}\{u(\xi)e^{j\frac{k}{2z}\xi^2}\}e^{-j\frac{2\pi}{\lambda z}x\xi}d\xi \quad (5)$$

$$\cong\frac{e^{jkz}}{j\lambda z}e^{j\frac{k}{2z}x^2}\int_{-\infty}^{\infty}u(\xi)e^{-j\frac{2\pi}{\lambda z}x\xi}d\xi \quad (6)$$

Note that in this situation, the lens acts as a collimator not a Fourier transformer. The two Fourier transforming situations correspond to the receiving and transmitting modes. Here, the Fourier transform using a lens in receiving mode will be analyzed and compared with the computation of Fourier transform using a personal computer.



(a)



(b)

Figure 1. Fourier transform pairs. (a) receiving mode (the lens Fourier transforms the wave from lens aperture) (b) transmitting mode (the lens collimates the ray from the point source)

III. ROTMAN LENS FOR FOCUSED BEAMS

3.1Rotman Lens for focusing a target

By adding the array of voltage-tunable phase shifters between a Rotman lens and an antenna array, we can focus the lens to the plane of an object as well as its back focal plane and use an array of detectors to map out an object image. The Rotman lens can be used to do the spatial processing that resolves the position of the reflected wave in an inexpensive way. The merits of the lens, wide-angle capability, broad bandwidth, and relatively small phase error make it possible to control the off-normal incident angle without any mechanical movement at the expense of multiple sources or detectors. Using the array of phase shifters, we can focus the targets distributed in short range on the focal arc of the Rotman lens. From an optical point of view, the lens with phase shifters acts as a lens with a variable focal length as shown in Fig. 2. The beam incident at different angles is focused on detectors positioned at different points along the focal arc of the Rotman lens. The antenna array, the phase shifters, and the lens all image the reflected energy onto the detectors so as to form a one-dimensional image of the reflected energy as shown in Fig. 3.

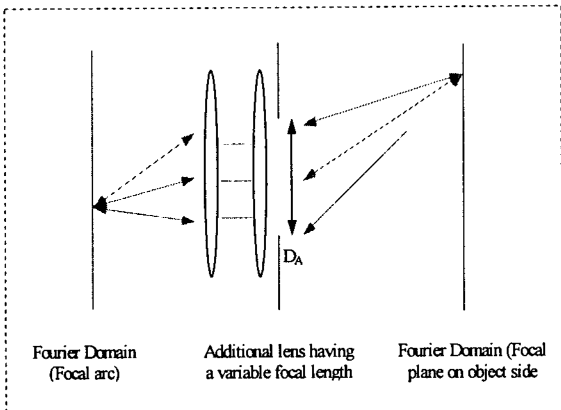


Figure 2. Focusing a target on object side with additional lens having a variable focal length

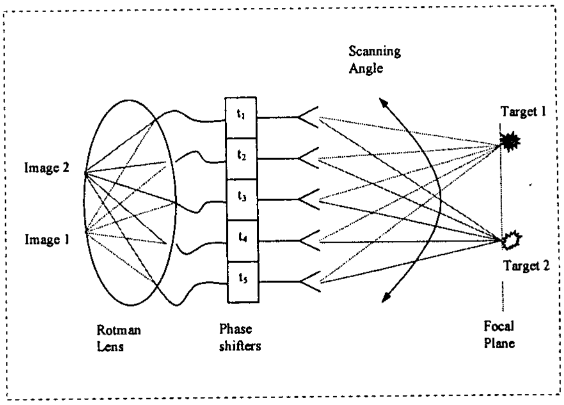


Figure 3. Schematic view of the short range detecting system

With a Rotman lens and phase shifters, it should be possible to detect mines, unexploded ordinance (UXO), and other buried structures with dielectric constants or conductivity that differ significantly from the surrounding material. Otherwise, for wireless communications, channel capacity can be proportionally increased by an antenna gain [3]. Furthermore, focusing beams can enhance the gain. The smaller the half power beamwidth (spot size) is, the more channels we can utilize.

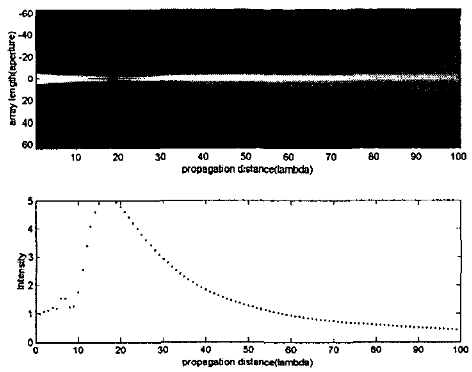
3.2 Beam Propagation Method for focused beams

In addition to the concept of adaptive focusing, a numerical method to see focusing phenomenon has been developed. The mentioned formulation is rough approximation to apply for numerical model of antenna propagation in the near field because the formulation does not include the aspect of polarization. However, in the area of optics, the BPM(beam propagation method) has been developed from the formulation and used to analyze propagation of a optical system. In this paper, the BPM(Beam Propagation Method) has been used to give simple inspection of focusing phenomenon from an aperture type antenna. According to the theory of Fourier optics, the beam propagation was assumed to be non-paraxial and coded using MATLAB. For this work, the two-dimensional Fresnel equation was simplified to a one-dimensional expression. In the Fourier domain, this convolution can be written as a product of Fourier transforms of an aperture function and the quadratic phase factor.

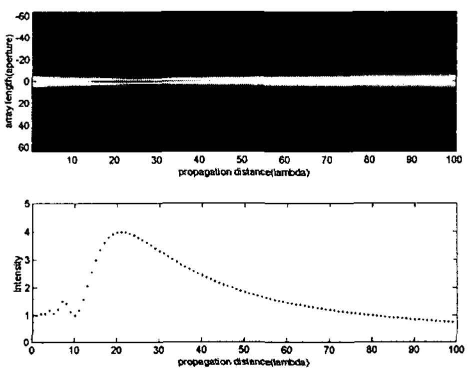
$$U(x) = \frac{e^{jkz}}{j\lambda z}\int_{-\infty}^{\infty} u(\xi) e^{j\frac{k}{2z}(x-\xi)^2} d\xi \qquad (8)$$

$$= \frac{e^{jkz}}{j\lambda z}\Im^{-1}\{\Im\{u(x)\}\times\Im\{e^{j\frac{k}{2z}x^2}\}\} \qquad (9)$$

Using Fourier Transform in MATLAB, Eq.(9) can be calculated and visualized at every step of propagation (z = 1λ). In addition, the length of the antenna array set to be 10λ and 1/2λ of spacing each antenna element. The spacing less than 1/2λ means that two signals are too correlated spatially to distinguish each other. The BPM has examined propagation of beams with the geometrical focal length of 20λ, 30λ, and 50λ and their propagation and intensity were computed and plotted.



(a)



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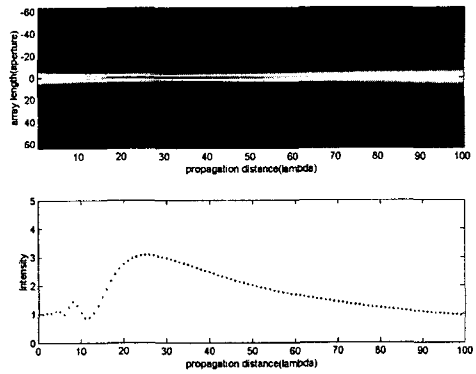

(c)

Figure 4. Beam propagations and their intensities of beams with different geometrical lengths (a) 20λ, (b) 30λ, and (c)50λ

For the beam with 20λ, 30λ, 50λ of geometrical focal length, as shown in Fig.4, the peak intensity occurs at 16λ, 20λ and 24λ, respectively. At these distances, their intensity on the center axis increases 5.11, 3.99, and 3.06 times as the power at the array surface, respectively. The half-power beamwidth (spot size) is about 1.10λ, 1.30λ, and 1.90λ, respectively. The focal distance is not equal to the distance at which peak intensity is observed. There is always a focal distance shift away from an aperture or an array.

Table 1. Beam propagation of focused beams with geometrical focal length of 20λ, 30λ, and 50λ

Focal Length	20λ	30λ	50λ
Distance	16λ	20λ	24λ
Focusing Int.	5.11times	3.99times	3.06times
Beamwidth	1.10λ	1.30λ	1.90λ

As expected from the fact that the focusing is a near-field phenomenon, all the focusing was obtained in a near-field region which extends to $2D^2/\lambda$ = 200λ (the size of the array, D=10λ). The results show the focusing is feasible in the short range with respect to the array length.

Ⅳ. DISCUSSION

By adding phase shifters to a Rotman lens, this lens can provide an efficient way to detect objects distributed in a near-field region. The results of BPM show roughly that the spatial resolution (spot size) can also be enhanced by using the Rotman lens with a series of phase shifters to focus the radiated or scattered energy from small spots positioned in short range. With regard to design factors such as system complexity, size, weight, and burden on signal processing, there are clear merits for using a Rotman lens over conventional ground-penetrating radar systems. These merits should make the system more compact and more cost-effective.

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