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Fully reflective photon sieve

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A B S T R A C T

Photon sieves (PS) have many applications and various designs in focusing light. However, a traditional PS only has a light transmissivity up to ∼25% and a focusing efficiency up to ∼7%, which hinder the application of them in many fields, especially for satellite remote sensing. To overcome these inherent drawbacks of traditional PSs, a concept of reflective photon sieve is developed in this work. This reflective photon sieve is based on a transparent membrane backed by a mirror. The transparent membrane is optimally a fully transparent material sheet with given refractive index and designed geometric thickness which has an optical thickness of a quarter incident wavelength (i.e. an anti-reflective coating). The PS-patterned pinholes are made on the transparent membrane. The design makes the light reflected from pinholes and that from zones of membrane material have 180° phase difference. Thus, light incident on this optical device is reflected and focused on its focal point. This device can have a reflectivity of ∼100% and a focusing efficiency of ∼50% based on numerical simulation. This device functions similar to a concave focusing mirror but can preserve the phase feature of light (such as that for the light with orbital angular momentum). It also has excellent wavelength-dependent property, which can exclude most of the undesired light from the focal point. A thin sheet of this component can perform the joint function of lenses and gratings/etalons in the optical path of a remote sensing system, thus is suitable for controling/filtering light in compact instruments such as satellite sensors. This concept is validated by the finite-difference time domain (FDTD) modeling and a lab prototype in this study.

1. Introduction

Photon sieves (PS) [1] have many applications [1–5] and various designs [6–8] in focusing light. However, a traditional PS only has a light transmissivity up to ∼25% and a focusing efficiency up to ∼7%, which hinder the application of them in many fields, especially for satellite remote sensing. To overcome the low transmission problem of regular photon sieves, we have developed a concept of a fully transparent photon sieve [9]. Based on the work in [9], a reflective PS concept is developed in this study, to improve the transmissivity and focusing efficiency, and for flexibility in application of the PS technique in compact optical devices such as satellite sensors, when a focusing of light by reflection is convenient in controling of light. Kalläne et al. [10] reported a type of reflective photon sieve constructed by an array of nanomirrors with an off-axis, off-normal incidence reflection geometry. Compared to transmission optical elements, their device's signal-to-background ratio is significantly increased by separating the first from other diffraction orders without drastically reducing the size of the smallest diffractive element. Their reflection photon sieve produces sharp foci at maximum contrast and offers the advantages of effective heat dissipation and a large working space above the focal plane. However, this device is not easily manufactured for specifically positioned discrete nanomirrors, and only less than 50% of the incident light is effectively reflected. In this study, we propose a new type of reflective photon sieve that is fully reflective and relatively easy to manufacture.

2. Method

In this study, the reflective photon sieve is based on a transparent membrane backed by a mirror as shown in Fig. 1. The transparent membrane is basically a fully transparent material sheet with given refractive index and designed geometric thickness which optimally has an optical thickness of a quarter incident wavelength (i.e. an anti-reflective coating). The PS-patterned pinholes are made

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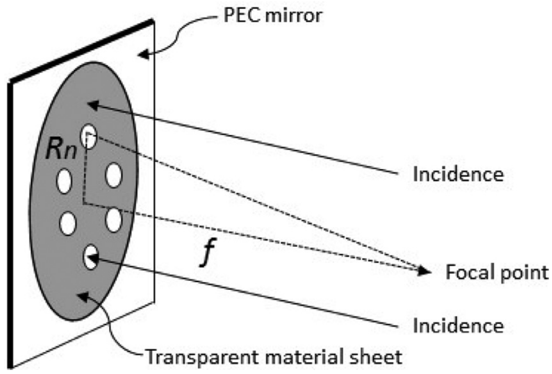

Fig. 1. Illustration of a reflective photon sieve: A sheet of fully transparent material with given refractive index, designed thickness, and patterned pinholes, backed by a reflecting perfect electric conductor (PEC) mirror.

on the membrane. The design makes the light reflected from pinholes and that from area of membrane material have 180° phase difference.

To make the reflected light to be focused on the focal point of the reflective PS, the thickness d and refractive index m of the transparent material membrane must satisfy [9]:

$$\frac{2\pi}{\lambda}m(2d) - \frac{2\pi}{\lambda}(2d) = (2k+1)\pi, \quad (1)$$

where λ is the wavelength of the light in free space and the integer $k=0, 1, 2, 3, \ldots, \infty$. Eq. (1) shows the phase difference between light transferring through the material and that through the pinholes and then reflected back through the material and pinholes by the mirror backing the material membrane as shown in Fig. 1. The geometric thickness of the transparent material membrane is

$$d = \left(\frac{2k+1}{m-1}\right)\frac{\lambda}{4}. \quad (2)$$

The optical thickness of the material membrane is then

$$D = md = m\left(\frac{2k+1}{m-1}\right)\frac{\lambda}{4}. \quad (3)$$

To make this material membrane anti-reflecting, $m(\frac{2k+1}{m-1})$should optimally be an odd integer. Due to the phase delay in the membrane sheet, light reflected by the membrane-mirror interface has 180° phase difference from the light reflected by the air-membrane interface, so it interferes and cancels all the light reflected by the air-membrane interface. Therefore, light reflected by the whole system is purely the light reflected by the membrane-mirror interface, which has the optimal expected phase delay for this design. Note that, even if $m(\frac{2k+1}{m-1})$cannot be made ideally close to an odd integer in practice, this only results in partial reflection from the air-membrane interface and slightly reduces the focusing efficiency.

The radial position of the pinholes in the n-th ring R_n is the same as that reported in our previous work [9]:

$$R_n = \sqrt{(2n-1)f\lambda + (n-0.5)^2\lambda^2}, \quad (4)$$

where f is the focal length of the photon sieve, and the ring number $n=1, 2, 3, \ldots, \infty$. The pinhole radius is set as $r_n = f\lambda/(4R_n)$ in this study [9,11,12]. The number of pinholes in the nth ring is given as $N^n_{hole} = 0.5\{\alpha + \exp[-1/2(\beta 2n/N_{ring})^2]\}\pi R_1 r_1/r_n^2$, where $\alpha = 1.0$,

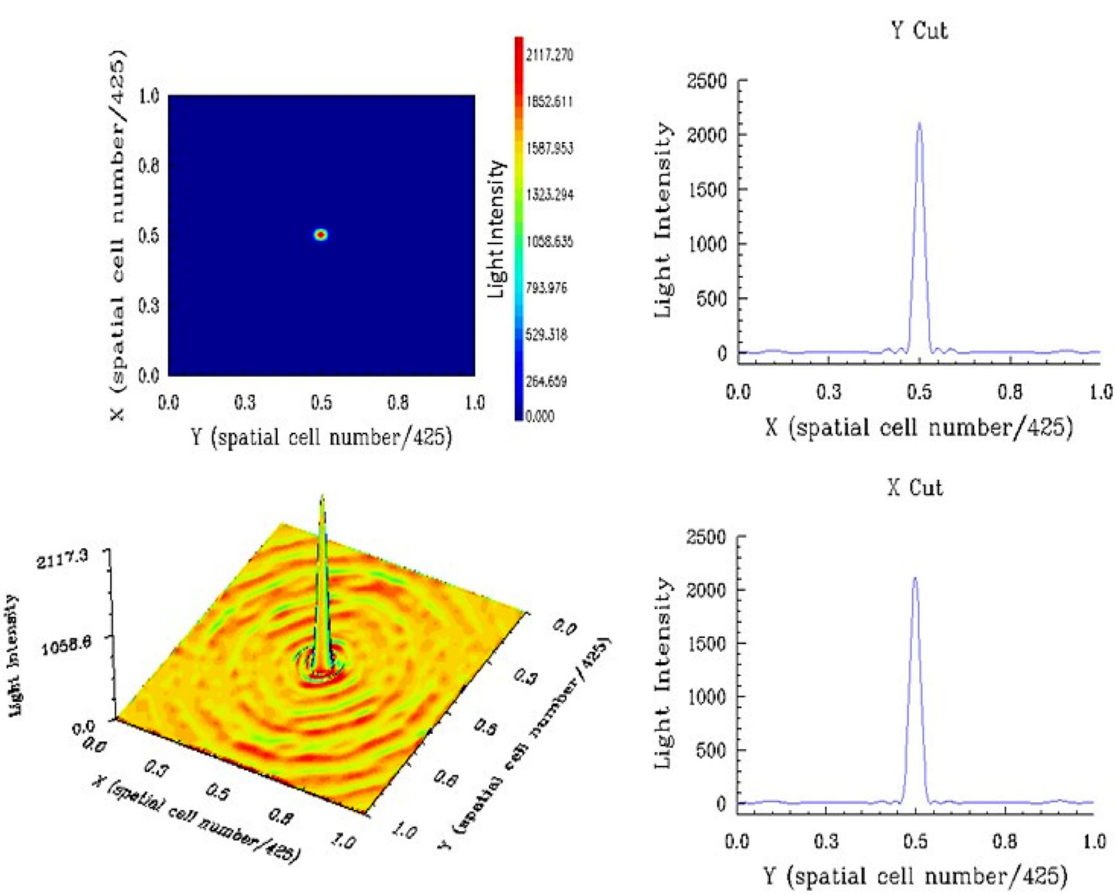

Fig. 2. Laser intensity on the reflective PS focal plane.