Embedded metal-wire nanograting for a multifunctional optical device

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Abstract: In this letter, an embedded metal-wire nanograting was fabricated and used to construct a multifunctional optical device. The basic function of the nanograting is broadband polarizing beam splitter. On the top of the nanograting surface, a homogeneity cladding layer was deposited, and metal-wires were deposited in the grating trench. This multifunctional optical device based on the artificial material is designed with a very simple structure, but with the function of variable optical attenuator, optical switch and variable optical power splitter. The experimental result as variable optical power splitter is presented.

OCIS code: nanograting, splitter, attenuator

Ⅰ. INTRODUCTION

The wire grid polarizer has been in existence for a long time [1], but there are still many limitations for its application in optical communication region due to the challenges of nano-scale fabrication and the poor adhesive, fragile properties of metal wire [2,3] . Recently we proposed a new PBS/C (Polarizing beam splitter/combiner) which is indicated by Figure 1. Based on unique properties of metal-wire nanograting the PBS/C consists of a series of fine parallel metallic lines embedded in substrate [4]. These wire arrays polarize efficiently when the width of the wires and the space between the wires are small enough compared to the wavelength of the incident light. As shown in Figure. 2, light polarized perpendicular (P beam) to the metal wires is largely transmitted and light polarized parallel (S beam) to the wires is reflected. The most common explanation of the wire-grid polarizer is based on the restricted movement of electrons perpendicular to the metal wires. If the incident wave is polarized along the wire direction, the conduction electrons are driven along the length of the wires with unrestricted movement. The coherently excited electrons generate a forward traveling as well as a backward traveling wave, with the forward traveling wave canceling the incident wave in the forward direction. The physical response of the wire grid is essentially the same as that of a thin metal sheet. As a result, the incident wave is totally reflected and nothing is transmitted in the forward direction. In contrast, if the incident wave is polarized perpendicular to the wire grid, and if the wire spacing is smaller than the wavelength, the Ewald–Oseen field generated by the electrons is not sufficiently strong to cancel the incoming field in the forward direction. Thus there is considerable transmission of the incident wave. The backward traveling wave is also much weaker leading to a small reflectance.

Thus most of the incident light is transmitted. The embedded grating and its detail fabrication process can be referred to our previous paper (reference 4). The novel metal grid polarizer beam splitter we developed using nanofabrication technique, which imbedded the metal grating under a homogeneity material as the substrate. The structure parameters optimum works were done with the help of commercial software G-Solver. Various metal layer thickness and air gap height were simulated with a given cladding layer thickness for transmission of P beam. Different duty cycle were simulated and revealed that larger duty cycle (w/Λ) will result in broader waveband of high efficiency P beam transmission, but the S beam reflection efficiency would be depressed if the duty cycle were too high.

Ag film thickness (t = 340 nm thick), air-gap (h1 = 480nm thick) and upper cladding SiO_2 layer (h2 = 380nm thick) with a 200nm period 0.75 duty cycle (w/Λ=0.75) were eventually chosen.

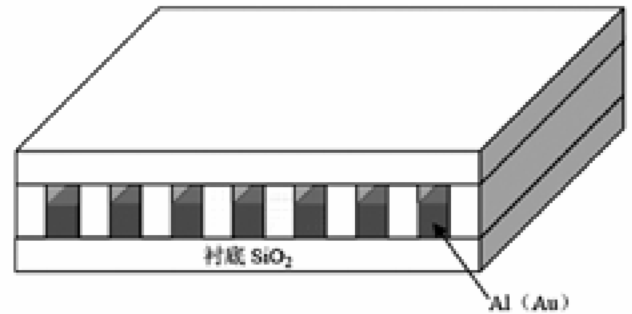

Fig. 1. The structure of the embedded metal-wire nanograting which consists of a series of fine parallel metallic lines embedded in substrate (SiO2)

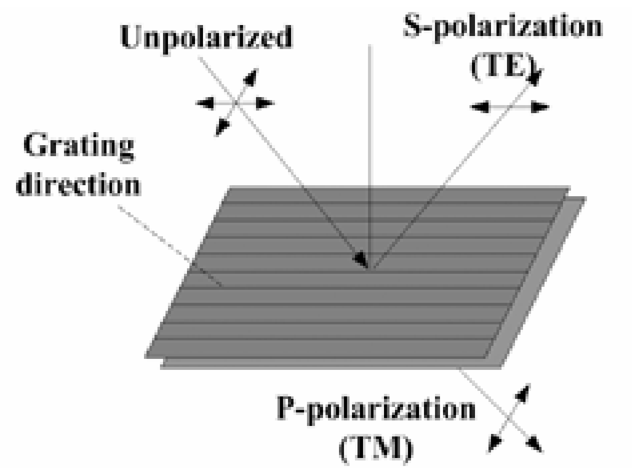

Fig. 2. Light polarized perpendicular (P beam) to the metal wires is largely transmitted through the nanograting and light polarized parallel (S beam) to the wires is reflected

It is worth to mention that we can use Ag to replace Au largely because the embedded wire grating structure, the Ag strip actually is hermetically sealed so that there isn't surface rust concerning. The fabrication was started from 0.2μm poly-methyl-methacrylate (PMMA) spin coated onto a quart glass substrate; E-beam lithography was then used to define a high-resolution grating with a period of 0.2μm and a duty cycle of 0.25. After development, 0.1μm Cr was deposited sequentially. The PMMA pattern was then lifted off to yield the 0.75 duty cycle grating metal mask. Subsequently, CHF_3/O_2 plasma was used to anisotropic reactive ion etching the quartz substrate with depth of 820nm. After stripped the residual Cr mask off the substrate in chemical etchant, 340nm Ag layer was deposited on the grating bottom and upper surface by physical sputtering, and the grating upper Ag layer was then etched away in Cl_2/Ar anisotropic plasma by slope the sample. The last process is deposition 380nm thick SiO_2 layer on the grating surface by slope the sample in PECVD chamber as the same way in the Cl_2/Ar anisotropic plasma etch process. The measured polarization properties were done using a 1550nm laser light with an incident angle of 20°. The measured transmission loss for P beam and reflection loss for S beam is 0.15~0.18 dB and the extinction ratio are larger than 40dB and 25 dB respectively. This embedded metal-wire nanograting not only provides high polarization efficiency for two orthogonal polarizations, but also can be operated with optical signal of wide incident angle tolerance and broad wavelength range. The unique property of this embedded PBS/C is that it can be adhered with other optical elements arbitrarily and can endure any physical and chemical impact on trial due to the steady homogeneity of the upper cladding layer. In addition, this structure gives a high adhesive ability for AR coating on the upper side. These features make this PBS/C desirable for optical communications application as well as other optical engineering.

In this letter, we present a new multifunctional device based on this embedded metal-wire nanograting. It has the function of variable optical attenuator, optical switch and variable optical power splitter. The device as a variable power splitter is fabricated and the experiment result is presented.

Ⅱ.A MULTIFUNCTIONAL DEVICE AND EXPERIMENTAL RESULTS

A proposed multifunctional device design is showed in Figure 3. It employs four pieces of the artificial material mentioned above. The two pieces at the left side work as PBS. They are glued back to back and their surfaces (top and bottom) are made with metal-wire having the same orientation embedded in nanograting. The other two pieces at the right side work as PBC. They have exactly the same structure but their grating orientation is perpendicular to the left side. The incident light from the first fiber collimator at input port 1 is separated into two orthogonally polarized beams (M1, M2) by the left side PBS (A). The reflected S beam will be reflected again by the top reflector then it will hit the right side PBC (B) from the top. The transmitted P beam will be reflected by the bottom reflector and then hit the right side PBC (B) from the bottom. Because the right side PBC (B) is designed to be perpendicular to the left PBS (A), the two beams will combine together and go to output port 1.

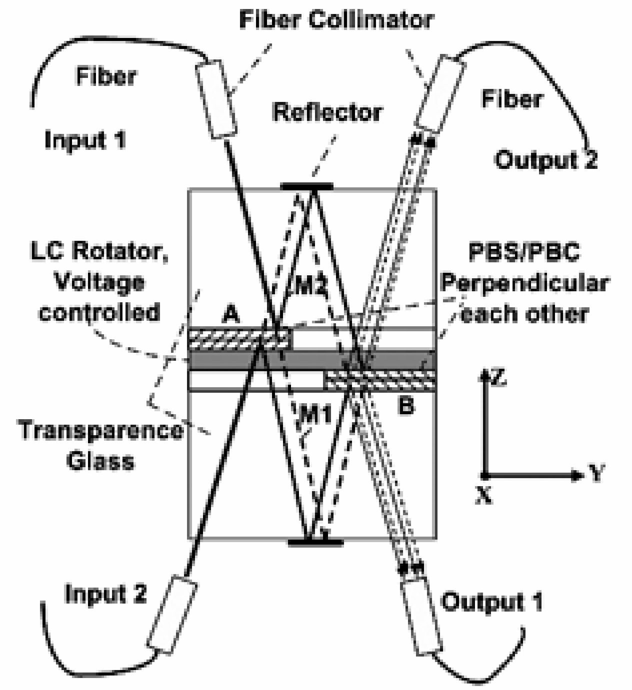

Fig. 3. Multifunctional device based on embedded metal-wire nanograting.

It is worth to mention that a single piece metal-wire grating couldn't provide symmetrical performance when the light beam hit it from top and bottom surfaces, so that two pieces back to back glued together is necessary from the point of view of practical application. The drawback of this design is that insertion loss for the transmission light beam will slightly increase. Additional benefit is that the extension ratio of transmission beam get improved at the same time.

No matter what polarization state the input light is, after it passes through the PBS (A), it will be separated into two polarization lights (M1, M2). Their vibrations are perpendicular, and the sum of the intensity of them is invariable. Supposing the intensity value of input light is 1, we use the Jones matrix method to calculate the intensities of output lights. According to the coordinate system in Fig.3, we suppose the Jones matrixes of two lights M1 and M2 are

$$M1=\begin{pmatrix}\cos\alpha \\ 0\end{pmatrix} \quad (1)$$

$$M2=\begin{pmatrix}0 \\ \sin\alpha\end{pmatrix} \quad (2)$$

When we insert a variable LC (liquid crystal) polarization rotator unit between the PBS and PBC, both of light beams pass through the LC unit only once. If there is a certain voltage applied on the LC unit, the S and P beam polarization angle could rotate. Supposing the ordinary refractive index of the LC unit is n_o, and the extraordinary refractive index is n_e, the angle that the polarization beams rotate is θ, we can get the Jones matrix of LC:

$$MC=\begin{pmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{pmatrix} \cdot \begin{pmatrix} e^{i\cdot\frac{n_e}{n_e-n_o}\cdot\pi} & 0 \\ 0 & e^{i\cdot\frac{n_o}{n_e-n_o}\cdot\pi}\end{pmatrix} \cdot \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix} \quad (3)$$

PBC (B) can be regarded as an analyzer. According to the Jones matrixes of these components, the Jones matrixes of last two output lights can be worked out:

$$M_{output1}=\begin{pmatrix} \sin\alpha\cdot\left(\cos^2\theta\cdot e^{i\cdot\frac{n_e}{n_e-n_o}\cdot\pi}+\sin^2\theta\cdot e^{i\cdot\frac{n_o}{n_e-n_o}\cdot\pi}\right) \\ \cos\alpha\cdot\left(\cos^2\theta\cdot e^{i\cdot\frac{n_e}{n_e-n_o}\cdot\pi}+\sin^2\theta\cdot e^{i\cdot\frac{n_o}{n_e-n_o}\cdot\pi}\right)\end{pmatrix} \quad (4)$$

$$M_{output2}=\begin{pmatrix} \sin\alpha\cdot\cos\theta\cdot\sin\theta\cdot(e^{i\cdot\frac{n_e}{n_e-n_o}\cdot\pi}-e^{i\cdot\frac{n_o}{n_e-n_o}\cdot\pi}) \\ \cos\alpha\cdot\cos\theta\cdot\sin\theta\cdot(e^{i\cdot\frac{n_e}{n_e-n_o}\cdot\pi}-e^{i\cdot\frac{n_o}{n_e-n_o}\cdot\pi})\end{pmatrix} \quad (5)$$

From (4), (5), the intensities of the two lights are:

$$I_{output1}=|M_{output1}|^2=\cos^2 2\theta \quad (6)$$

$$I_{output2}=|M_{output2}|^2=\sin^2 2\theta \quad (7)$$

And $I_{output1}+I_{output2}\equiv 1$.

When θ= 45°or 90°, which means $I_{output1}$=0 or 1, $I_{output2}$=1 or 0, the input light can only go to one output. This is an essential 1x2 switch. If θ is not integral times of 45°, the S and P beams polarization would become S+P beams, therefore we could get two outputs at both output ports. This is an essential 1x2 VPS (variable power splitter). This splitter is a polarization independent device, since the intensities of the two output lights are independent of α.

When we only deploy one input and one output, this is an essential VOA (variable optical attenuator). Further more, we can add another input port at the left bottom corner of this device, and this input light may go to output port 2 or output port 1, therefore, this is an essential 2x2 switch and it may also be used as a two-way mixer. We have built a prototype of this device, and the performance meets most of the engineering application requirements. A total insertion loss less than 1.1 dB has been achieved and PDL (Polarization dependent loss) is only about 0.1 dB. For the VPS, 30dB tunable range has been achieved, this means the cross talk for the switch and the dynamic range for the VOA is also about 30dB.

We also used a rotate able half wave plate to replace the LC unit. When the two beams' polarization directions are parallel to the wave plate axis, there is no polarization state change after the two beams pass through the wave plate. When the angle between the beams polarization directions and the wave plate axis is 45°, the S and P beams will turn to each other after passing through the wave plate, and when it is between 0~45° the device will be a variable power splitter. Taking advantage of the low insertion loss of the wave plate, we already made a 1x2 manual variable power splitter with insertion loss less than 1.0dB. In order to enhance the controlling resolution of the VPS, we use a retarder to control the wave plate rotation. When the retarder rotates thirty-two circles, the wave plate rotates one circle. As shown in Figure 4, in order to change the output power a period , the retarder should rotate eight circles so that the wave plate rotates 1/4 circle (90°). It is a purely passive, low cost and practical device, and the retarder is adjustable with a screwdriver. It should be noted that various variable OPS designs have been proposed previously [5-7], including fiber variable OPSs, Y-junction waveguide variable OPSs, OPSs using an embedded V-groove, OPSs using variable transmission /reflection film technology, OPSs using the multicasting capability of opto-very-large-scale- integrated (Opto-VLSI) technology. However, these methods suffer from disadvantages such as small variable range, high polarization dependence, and low controllable resolution. Because their application value is limited, few if any of these components have been commercially available before.

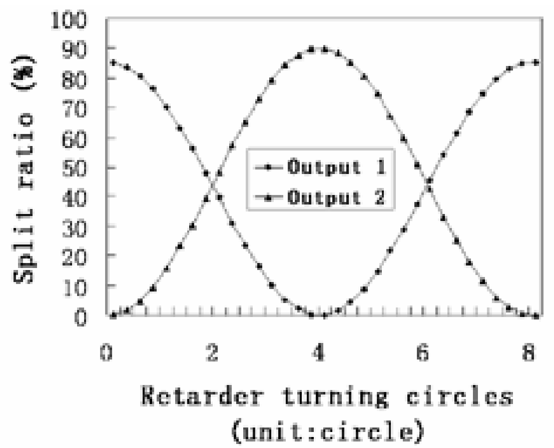

Fig. 4. The measured output power as a function of the retarder rotation when the device works as variable power splitter

Ⅲ.CONCLUTION

This paper introduces a multifunctional device design based on a novel PBS artificial material. The multifunctional device has the function of VOA, switch and VPS. This novel material consists of upper cladding layer, air gap layer and metal-wire grating layer. It is desirable for practical applications because of its excellent PBS/C performances, its ability of being arbitrarily adhered with other optical elements, and the highly adhesive ability of the AR coating on the surface. Our experimental work shows that this device has low insertion loss, low polarization dependent loss, wide dynamic range, small package and low cost. Due to the big potential market demand, it may become a very important application in nano-fabrication technologies.

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