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Design and fabrication of metal-wire nanograting used as polarizing beam splitter in optical telecommunication

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We developed a metal-wire nanograting device as a polarizing beam splitter (PBS) for the optical telecommunication applications. Effective Medium Theory (EMT) was used for initial design and Rigorous Coupled Wave Analysis (RCWA) was used for optimization. We fabricate metal-wire nanogratings on glass substrate using nanoimprint lithography (NIL) and reactive ion etching (RIE) process. Experimental investigation shows that the PBS device has uniform performance with broadband wavelength and wide variations in the angle of incidence. These features with their small size make these PBSs desirable for use in optical telecommunication and allow more compact component designs.

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1. Introduction

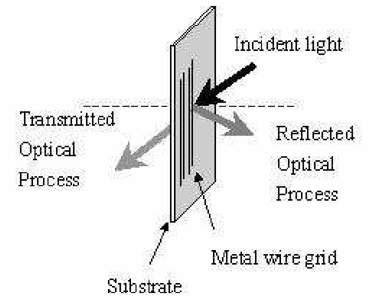
Polarizing beam splitters (PBS) are essential optical devices for most optical systems and optical networks. Conventional polarizers and PBS are bulky optics, which is a disadvantage for many applications that require compact size for efficient packaging. The other critical thing to optical networks is that they are expensive in large part because optical components themselves are expensive. Today's optical devices lag far behind their semiconductor counterparts in integration, density, diversity, manufacturability, availability and reliability. While electronics manufacturing has evolved from physical assembly of discrete components to the high-volume manufacture of optical-component integration: hybrid and monolithic [1]. Hybrid integration is a packaging-based bringing together carefully selected, compatible optical components on a precise bench structure, to create sophisticated integrated optical modules. Monolithic integration is wafer-based chip to create integrated functionality.

Grating nanostructures with period smaller than wavelength, known also as subwavelength optical elements (SOEs), have the potential to replace or improve conventional optical elements [2]. In addition, it allows increased flexibility in optical design while fitting for hybrid integrated and reducing parts counts. They can be used as anti-reflection (AR) surfaces for visible and near infrared spectrum applications [3,4]. Another application is the polarization effect. This effect is enhanced by the presence of a subwavelength metal wire grid [5]. Work is in progress on grating structure polarizer with periodicities approximate 150 nm for covering the complete optical telecom spectrum with much better characteristics. Developments in microlithography and associated technologies now make it possible to put these principles into practice and in particular to produce"artificial media". As a result, the subject of subwavelength structures now attracts a great deal of research interest with a view to extending the possibilities of waveguides, optical fibers and electro-optical material.

In the present paper we report the design and fabricated metal wire nanogratings with the function of polarizing beam splitter for the optical telecommunication applications.

2. Principle and modeling

Consider a wire-grid polarizer consists of a series of fine parallel metallic lines coated on glass substrate as shown in Fig. 1. These wire arrays polarize efficiently when the dimensions of the wires and spacing are small compared to the wavelength of the incident light. Light polarized parallel to the metal wires is reflected. Light polarized perpendicular to the wires is largely transmitted. The most common explanation of the wire-grid polarizer is based on the restricted movement of electrons perpendicular to the metal wires [6]. 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.



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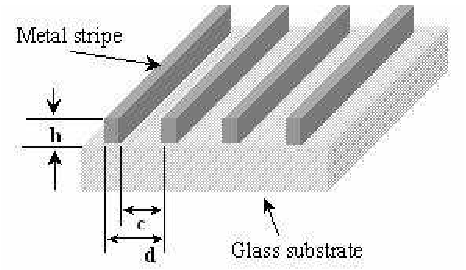

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Fig. 1. (a) Schematic of the nanograting PBS, where TM polarized light is transmitted and TE polarized light is reflected. (b) Metal wire nanograting model.

Because the grating period is far smaller than wavelength, the traditional diffraction theory is not fit for it again. We used Effective Medium Theory (EMT) for initial design and rigorous coupled wave analysis (RCWA) [7] for optimization of the polarizing beam splitter.

When the period of the grating is sufficiently small compared with the wavelength, the whole structure behaves as if it were homogenous and equivalent to one birefringence film [8] Consider a one dimensional grating composed of two materials of refractive indices n_1 and n_2 with duty cycle f (f = $\text{width}_{(\text{material of n1})}$ / period); the effective indices are given by [9]

$$n_{/\!/} = [\, f n_1^2 + (1 - f)\, n_2^2 \,]^{1/2}, \quad (1)$$

$$n_{\perp} = n_1 n_2 [\, f n_2^2 + (1 - f)\, n_1^2 \,]^{-1/2}. \quad (2)$$

By choosing the material and adjusting the duty cycle f, a birefringence effect can be achieved that is much larger than that achieved with standard optical materials.

3. Simulation and optimization

For a general polarizing beam splitter, four parameters are used to characterize the polarizing beam splitter's performance: transmission extinction ratio (Ext.T), reflection extinction ratio (Ext.R), transmittance (T_{TM}), and reflectance (R_{TE}). Transmittance (T_{TM}) is the power transmission coefficient for TM (electric-field vector perpendicular to the wire) polarized light. Reflectance (R_{TE}) is the power reflection coefficient for TE (electric-field vector parallel to the wire) polarized light. Ext.T is defined as 10log (T_{TM}/T_{TE}), in which T_{TE} is the power transmission coefficient for TE polarized light. Ext.R is defined as 10log (R_{TE}/R_{TM}), in which R_{TM} is the power reflection coefficient for TM polarized light. Ext.R is a key parameter for characterizing the polarizing beam splitter, since Ext.R is usually much lower than Ext.T due to existence of small reflectance of TM polarized light. Once the period of the wire grid is determined, there is always an inherent rade-off between achieving high Ext.T and high T_{TM} because achieving higher Ext.T requires more metal volume, which leads to more absorption and thus lower $T_{TM.}$ R_{TM} and Ext.R are also influenced by the metal thickness.

In this work, a period of ～150 nm is used for optical telecommunication (900～1700 nm) applications. different metal layer thickness *h* were simulated (using RCWA [6]) and are shown in Fig. 2 and Fig. 3, revealing that about 100 nm thickness or 600～700 nm thickness results in a high extinction ratio and low insertion loss of both polarization, but for grating period of 150 nm, metal layer with thickness above 600 nm is difficult to fabricate. In order make the fabrication process easy and get good polarization properties, metal layer thickness 100 nm and grating period 150 nm with duty cycle 50% were eventually chosen.

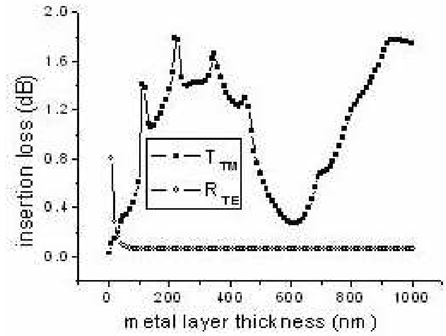

Fig. 2. Insertion loss of TM and TE polarized light (T_{TM} & R_{TE}) as a function of metal layer thickness h.

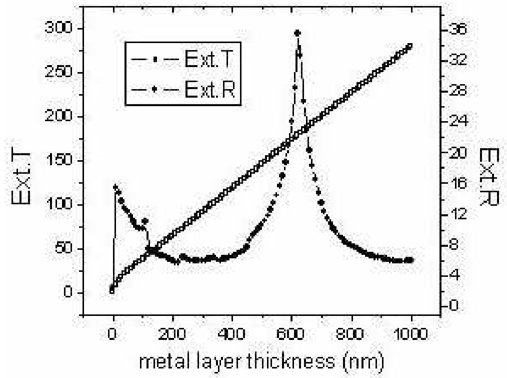

Fig. 3. Extinction ratio of transmission and reflection (Ext.T & Ext.R) as a function of metal layer thickness h.

4. Fabrication results and discussion

We have used nanoimprint lithography (NIL) to fabricate the metal wire grating structure on quartz substrate. First, an Al film was deposited on a glass substrate. Then 0.2 μm thick poly-methyl-methacrylate (PMMA) was spin coated onto a quartz substrate to form a shadow mask. A thermal nanoimprint process was then used to define a high-resolution grating with a period of 150 nm and a duty cycle of 0.5. After imprinting, the residual layer was removed by O2 plasma and Al was etched by RIE. The final result of the grating in our experiment is shown in Fig. 5. It is worth mentioning that Al is used in our experiment because it adheres well to substrates and is relatively easy to deposit. Gold could be used to replace Al in this experiment, but a thin layer of a different metal such as titanium is often required because the gold will not adhere to the substrate, complicating the design and fabrication process.

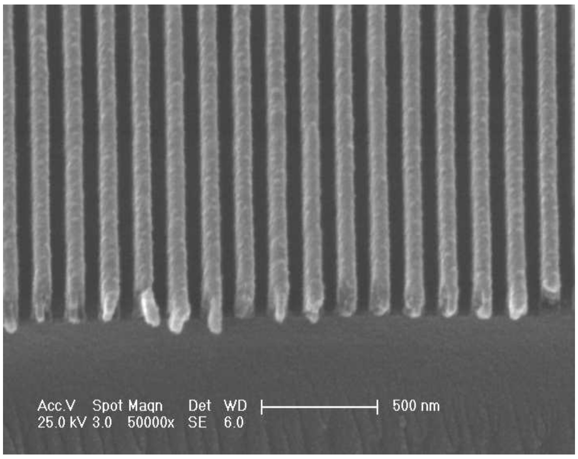

Fig. 5. Scanning electron microscope photographs of the grating sample with a period of 150 nm and a duty cycle of 0.5.

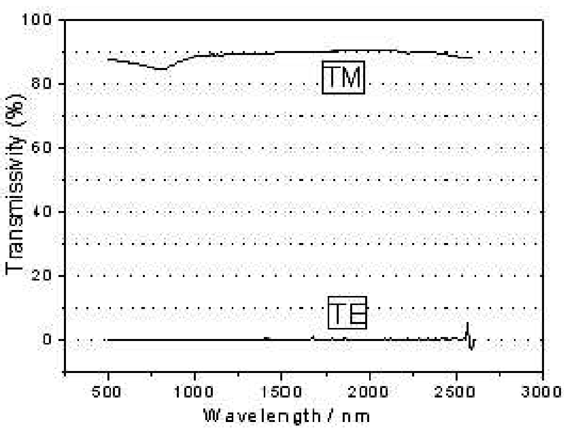

Fig. 6. Transmission spectrum measured for TE and TM wave.

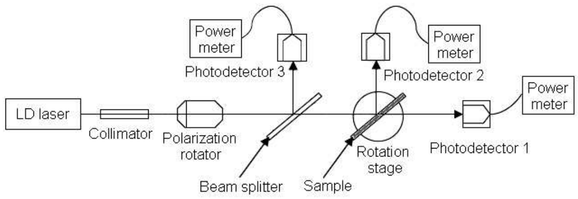

Fig. 7. Schematic diagram of the experimental setup for the efficiency measurement of the fabricated embedded nanograting.

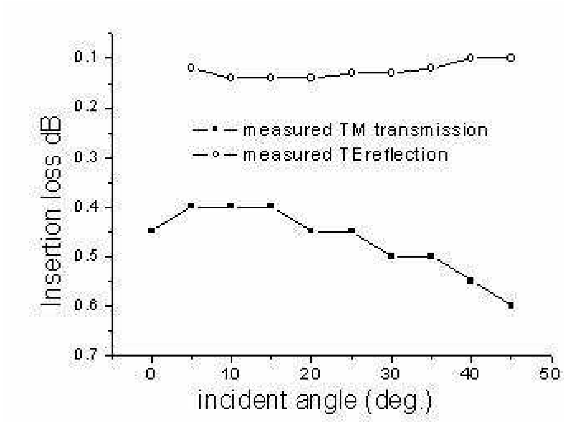

Fig. 8. Experimental result of insertion loss measured as a function of incident angle.

The fabricated grating was measured by spectrophotometer (Lamida 900). Transmission spectrum (500～2500 nm) for TE and TM wave are shown in Fig.6, revealing that the grating has broadband performance in whole optical telecommunication wavelength. To investigate the influence of incident angle, we used a measure setup shown schematically in Fig. 7 with a 1550nm wavelength light source. The beam was focused onto the fabricated grating, and its input polarization was controlled by a polarization rotator. Three photodetectors were then used to measured the transmission, the reflection and the incidence reference light power simultaneously. The sample was mounted on a controllable rotation stage. The measured insertion loss as a function of incident angle are shown in Fig. 8. (The incident angles from 5° beginning for reflection efficiency measured) It can be seen from Fig.8 that the grating has very broad band for incident angle, which give great angle tolerate for device package. The efficiency of TM transmission could be improved by adding an anti-reflective coating on the surface of the grating. These works will be discussed in detail in future publications.

5. Conclusions

In conclusion, we have developed a PBS device based on metal-wire nanograting. TE polarization will be reflected while TM polarization will be transmitted. Effective Medium Theory (EMT) was used for initial design and Rigorous Coupled Wave Analysis (RCWA) was used for optimization of the polarizing beam splitter. We fabricate metal-wire nanogratings on glass substrate using nanoimprint lithography (NIL) and reactive ion etching (RIE) process. Experimental investigation of the polarization effect for this grating is carried out. The polarizing beam splitter has uniform performance with broadband wavelength and wide variations in the angle of incidence. These features including the small size make it desirable for use in optical telecommunication and allows for more compact component designs.

Acknowledgements

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Reference

[1] M. Kawachi, IEE Proc. Optoelection, **143**, 257 (1996).
[2] M. Schnieper, M. T. Gale, C. Zschokke, Proc. of DOMO 2002, Tucson, USA.
[3] Ph. Lalanne, G. M. Morris, Nanotechnology **8**, 52 (1997).
[4] Y. Kanamori, M. Sasaki, K. Hane, Opt. Lett. **24**, 1422 (1999).
[5] B. Schnabel, E.-B. Kley, F. Wyrowskl, Opt. Eng. **38**, 220 (1999).
[6] E. Hceht, A. Zajak, Optics, 3rd ed. (Addison-Wesley, Longman, 1998).
[7] M. G. Moharam, T. K. Gaylord, J. Opt. Soc. Am. A **3**, 1780 (1986).
[8] A. Yariv, P. Yeh, Optical Waves in Crystal, Wiley, (1984).
[9] F. Flory, L. Escoubas, B. Lazarides, Appl. Opt. **41**, 3332 (2002).

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