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**Research Article**

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# Numerical Simulation of Metasurface Grating to Function as Polarization Modulator in Quantum Key Distribution Systems

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**Abstract:** Polarization modulation plays an important role in polarization encoding in quantum key distribution. By using polarization modulation, quantum key distribution systems become more compact and more vulnerable as one laser source is used instead of using multiple laser sources that may cause side-channel attacks. Metasurfaces with their exceptional optical properties have led to the development of versatile ultrathin optical devices. They are made up of planar arrays of resonant or nearly resonant subwavelength pieces and provide complete control over reflected and transmitted electromagnetic waves opening several possibilities for the development of innovative optical components. In this work, the Si nanowire metasurface grating polarizer is designed by COMSOL Multiphysics Software to operate in the visible region and transmit the transverse magnetic polarization of light. The same structure can be rotated by different angles, i.e., $90^o$, $45^o$, and $-45^o$ to mimic the function of polarization modulation in quantum key distribution systems. The designed structure has an extinction ratio of ~ 60000 and a wide angular tolerance range of ($-20^o$ - $20^o$).

**Keywords:** resonance grating; subwavelength grating; metasurfaces; wire-grid polarizer.

## 1. Introduction

Quantum key distribution (QKD) was initially suggested in 1984 and has advanced significantly over the past few decades in fiber and free space. QKD is a perfect solution for distributing an absolute secret key between two remote parties. It can be considered as one of the first practical applications that is based on single photons. Moreover, satellite-to-ground QKD and the satellite-relayed intercontinental quantum network have been successfully realized by the quantum science satellite, Micius [1,2]. QKD enables two spatially separated parties, i.e., Alice and Bob, to produce a private and secure cryptographic key based on the laws of quantum physics. This can be done by the exchange of qubits that are encoded into individual photons [3]. Polarization modulation plays an important role in polarization encoding QKD.

Polarization encoding is to a large extent employed in fiber-based QKD and free-space QKD, for which weak coherent pulses are typically encoded into four polarization states, i.e., horizontal $|H\rangle$, vertical $|V\rangle$, $|D\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$ and, $|A\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle)$ [1].

Mainly the multiple-laser scheme is widely used in QKD systems, where each required polarization state is prepared by an independent laser source. However, side-channel information leakage is the most critical issue that affects the performance of these systems [4].

Production of quantum key at competitive rates requires the high-frequency generation of polarization states, which is a challenge. Polarization controllers do not provide the GHz state frequencies needed for present-day QKD setups. The simplest fast QKD configuration for Alice consists of four independent laser sources, one for each state of polarization required, e.g. BB84 protocol [5]. But the indistinguishability of pulses emitted from different laser sources will be hard to guarantee, resulting in the system's vulnerability. Bob as well needs to modify the state of polarization arriving at his station to select the measurement basis [6].

A significantly higher repetition rate with inherent homogeneity in other photon dimensions can be achieved by using the external polarization modulation technique. Essentially, the concept of polarization modulation involves phase modification in particular polarization bases [1]. In order to prevent side-channel attacks a single laser source with an active polarization modulator is typically used. One option is to use the Pockels effect of fast electro-optical $LiNbO_3$ phase modulators to switch the polarization. This type of modulator is based on balanced interferometers. Two orthogonal polarization components enter different arms of the interferometer via a polarization beam splitter, after that one of the components experiences a phase shift induced by the modulator. As a result, two diagonal and two circular states can be generated [6]. Another option is based on the use of birefringent phase modulators in an in-line configuration [3]. In these schemes, the photons are injected in the phase modulator that basically consists of $LiNBO_3$ crystal with a polarization state that is diagonal with respect to the optical axis of the modulator's crystal. By applying a bias voltage, the ordinary and extraordinary refractive indices of the crystal vary independently, where the relative phase between the $|H\rangle$ and $|V\rangle$ polarization is controlled. This option presents several disadvantages. First, the polarization modulation is highly sensitive to temperature and bias voltage drift and requires active stabilization. A second issue is related to the polarization mode dispersion (PMD) induced by the birefringence, which reduces the degree of polarization for short pulses, i.e., decreasing the modulation performance. Thirdly, high voltages are required for these modulators to induce the required polarization modulation [7,8].

Other types were proposed such as a self-compensating polarization encoder based on $LiNBO_3$ phase modulator inside a Sagnac interferometer [9]. Using homogeneous birefringent metasurfaces that are composed of identical elements with varied responses for two linearly polarized orthogonal components ($E_x$ and $E_y$) is the new technique for polarization conversion [9].

Metasurfaces are composed of distinctively designed subwavelength units in a two-dimensional plane, providing a new principle to design ultra-compact optical elements that show great potential for miniaturizing optical systems. By employing metasurfaces, various parameters of the light wave can be manipulated, such as pixelated polarization manipulation in the subwavelength scale which is a distinguished ability of metasurfaces compared to traditional optical components. But, plasmonic-type metasurfaces have an intrinsic ohmic loss that highly hinders their broad applications due to their low efficiency. Accordingly, metasurfaces composed of high-refractive-index all-dielectric antennas have been proposed to achieve highly efficient optical devices [11].

Compared to conventional optical components that provide wavefront engineering by phase accumulation through light propagation in the medium, metasurfaces have new degrees of freedom to control the phase, amplitude, and polarization response with subwavelength resolution. In addition, wavefront shaping within a distance much less than the wavelength can be accomplished. Their exceptional optical properties have led to the development of versatile ultrathin optical devices [12].

To support extensive phase coverage and low resonance loss, the materials used for dielectric metasurfaces must have a high refractive index (n) and low extinction coefficient (κ). The main materials used for dielectric metasurfaces include Silicon (Si), Gallium nitride (GaN), Titanium dioxide ($TiO_2$), and Silicon Nitride (SiNx). Si-based metasurfaces are regarded as low-cost metasurface platforms because Si is an abundant element and can be easily processed using standard CMOS-compatible manufacturing techniques [13].

In this work, Si nanowire metasurface grating polarizer that controls the wavefront of incident light is designed and its performance is numerically investigated. COMSOL Multiphysics Software is used to design the proposed structure. The metasurface grating is designed to transmit the transverse magnetic (TM) polarized light. The same structure transmits linearly polarized light with an electric field vector oriented at $0^o$, $90^o$, $45^o$, and $-45^o$ by changing the orientation of the grating. The designed structure can be used for obtaining four states of polarization of light passing through it, so it can replace polarization modulators in QKD systems.

## 2. Theory of Operation

Guided-mode resonance is a phenomenon that happens at subwavelength grating structures. The term "guided-mode resonance" appeared in 1990 by Wang et al. in an attempt to clearly communicate the fundamental physics governing these phenomena [14].

Figure 1 illustrates the resonant grating waveguide structure. These periodic photonic lattices are also referred to as "metasurfaces" or "metamaterials" in which periodically aligned subwavelength-scale features enable manipulation of incoming electromagnetic waves in a desired manner. The resonant grating waveguide consists of a substrate, a waveguide layer, and a grating layer. When a light beam is incident on such a structure, part of the beam is directly transmitted through the structure, and part is diffracted by the grating and is trapped in the waveguide layer. Part of the trapped light in the waveguide layer is then rediffracted out and it interferes destructively with the transmitted part of the light beam. Resonance happens at a specific wavelength and angular orientation of the incident beam; namely, complete interference occurs, and no light is transmitted [15].

At resonance, coupling is achieved between the diffracted light by subwavelength grating, and the waveguide mode and propagates in the lateral direction. During propagation, the mode leaks out due to the presence of the grating on the waveguide. The constructive (destructive) interference based on the phase difference between the outgoing "leaky" wave and the directly reflected wave from the grating surface forms a reflection (transmission) resonance in the optical spectrum of the device. Accordingly, the guided mode resonance device can be seen as operating in light capture, storage, and release modes. The guided-mode resonance emphasizes the capture of photonic energy whereas leaky-mode resonance emphasizes the release of photonic energy [14].

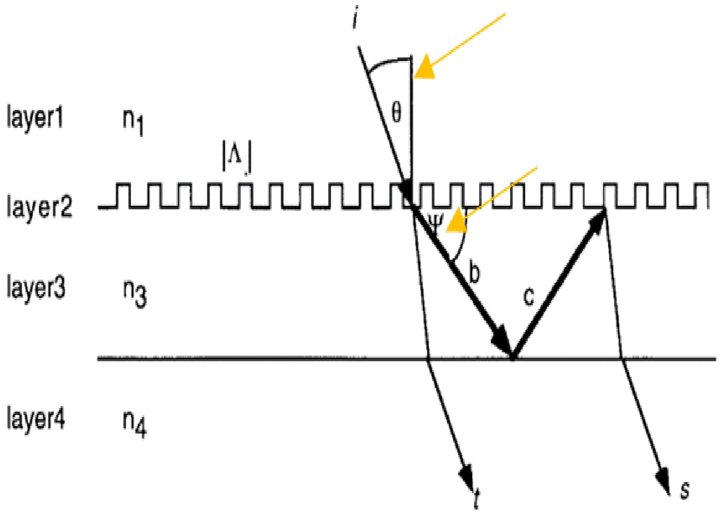

**Fig. 1:** Grating waveguide structure. Transmitted wave t and diffracted wave s originating from the incident wave i destructively interfere at resonance [15].

## 3. Design and Investigation of Nanowire Metasurface Grating Polarizer

The schematic structure of the designed metasurface grating polarizer is shown in Fig.2. The structure is designed in the visible region. Based on the effect of guided-mode resonance, the metasurface structure passes the TM polarized light and blocks the TE one.

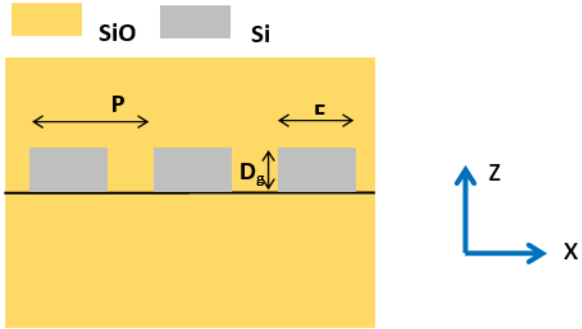

**Fig. 2:** Metasurface grating polarizer structure.

The structure consists of Si grating on a $SiO_2$ substrate of 1000 nm thickness. The grating is covered by air. The refractive indices of Si and $SiO_2$ are (3.8841 and 1.4570) at λ=632 nm respectively. Many optimization methods are used to design the optical components based on metasurfaces such as topology optimization, Bayesian optimization, genetic algorithm, neural networks, and particle swarm optimization method [16]. The last method is very popular for the optimization of metasurface structures especially those consisting of nanowire grating. In this work 2-D framework with Monte Carlo solver optimization supported by COMSOL was used to find the optimum dimensions of the metasurface grating polarizer. In the Monte Carlo solver optimization method, the points are sampled randomly within a uniform distribution by a user-specified box. The Monte Carlo solver is efficient in gathering statistical data for the variations in design parameters by analyzing the range of value of the objective function that is maximized (or minimized) considering several constraints. The optimum dimensions will give maximum transmittance for TM polarization and minimum transmittance for the transverse electric (TE) polarization. The optimum dimensions for P, Dg, and FF are 368 nm, 82 nm, and 0.2465 respectively. Figure 3 (a) shows the transmittance of zero-order TM and TE polarization. The extinction ratio (ER) which is defined as $(\mathrm{ER} = \mathrm{T_{TM}}/\mathrm{T_{TE}})$ is shown in Fig.3 (b). Maximum ER ~ 60000 at λ= 632 nm.

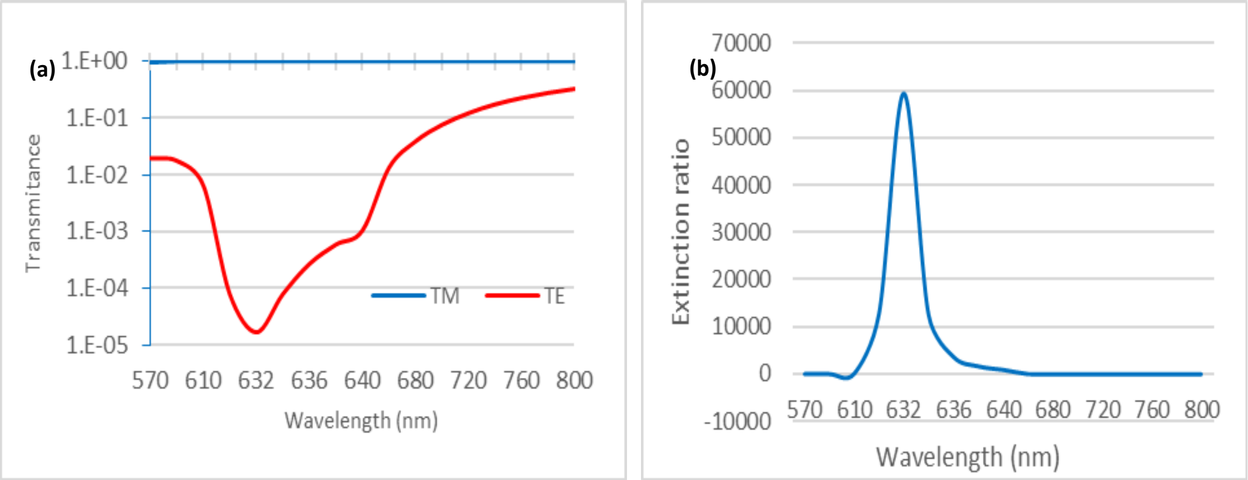

**Fig. 3:** Metasurface grating polarizer a) Transmittance of TM and TE polarized states (b) ER of metasurface grating polarizer where P, $D_g$, and FF are 368 nm, 82 nm, and 0.2465 respectively.

The maps of electric field distribution for TM and TE transmission as a function of incidence angle are shown in Fig.4 (a) and (b) respectively. The high transmission and low transmission are shown by red areas and blue areas respectively.

The proposed structure can be rotated by a specific angle so that the orientation of the electric field can be varied which means different polarization of light can be obtained. Figure 5 shows four orientations for the designed metasurface grating polarizer, i.e., $0^o$ (the proposed structure), $90^o$, $45^{o,}$ and $-45^o$. The proposed structure can be fabricated and mounted on a suitable rotating base that can be rotated randomly to obtain the polarization states of light in many protocols in QKD systems.

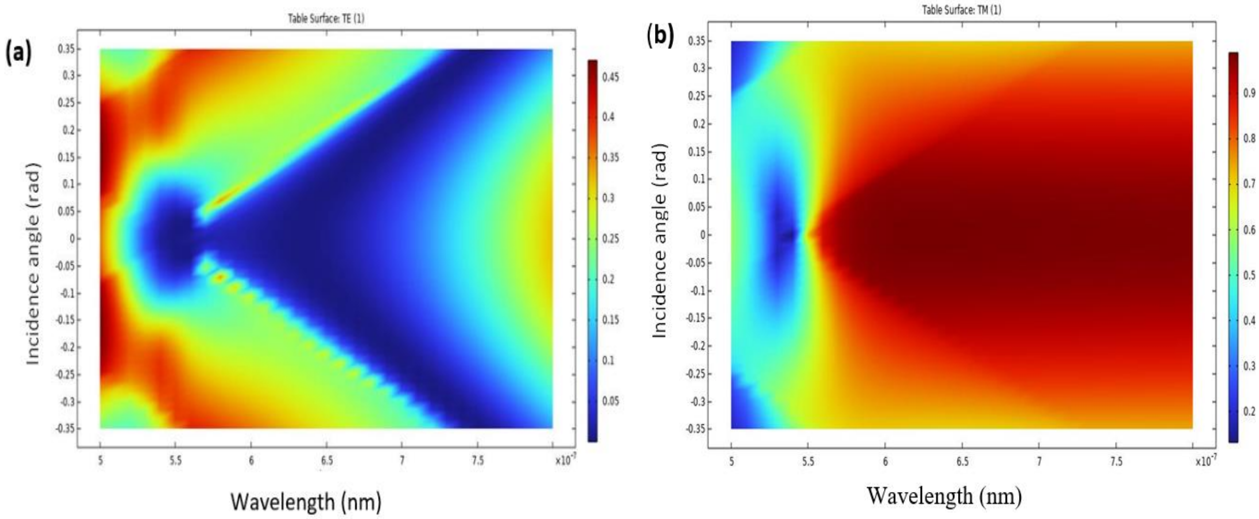

**Fig. 4:** Transmission map of metasurface polarizer as a function of incidence angle for (a) TM and (b) TE.

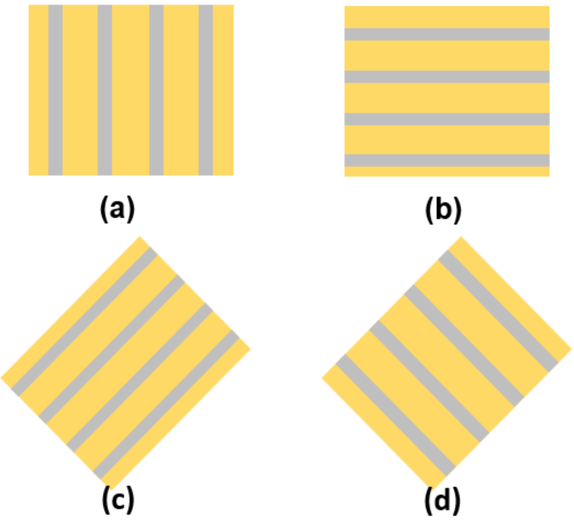

**Fig. 5:** Samples of Metasurface grating.

## 4. Conclusions

A Silicon nanowire metasurface grating polarizer operating in the visible region has been numerically designed and its performance to transmit TM-polarized light has been investigated. The design structure showed high ER ~60000 and wide angular tolerance ranging from -20° to +20°. This structure can be used in QKD systems to replace polarization modulators which a key optical component needed to provide the polarization state for photon encoding.

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# تصميم رقمي لمحزز حيود بسطح فعال يعمل كمضمن استقطاب لمنظومات توزيع المفتاح الكمي

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**الخلاصة:** يلعب مضمن الاستقطاب دورا هاما في ترميز الاستقطاب في توزيع المفتاح الكمي. باستخدام مضمن الاستقطاب، تصبح انظمة توزيع المفتاح الكمي اكثر ترتيبا وامانا حيث يتم استخدام مصدر ليزري واحد بدلا من استخدام عدة مصادر ليزرية قد تتسبب في حدوث هجمات تتسرب من خلالها المعلومات. ادى التطور في الخصائص البصرية الاستثنائية للاسطح الفعالة الى ظهور اجهزة بصرية فائقة الصغر ومتعددة الاستخدامات. حيث تتكون هذه الاسطح الفعالة من مصفوفات مستوية لاجزاء بابعاد تعادل اجزاء من الطول الموجي في حالة رنين او قريبة من الرنين توفر تحكما كاملا في الموجات الكهرومغناطيسية المنعكسة والمرسلة مما يوفر امكانيات عديدة لتطوير تراكيب بصرية مبتكرة. في هذا العمل، تم تصميم مستقطب من محزز حيود لسطح فعال من مادة السليكون باستخدام برامجيات كومسل ذو الفيزياء المتعددة ليعمل في المنطقة المرئية ويسمح بمرور الاستقطاب المغناطيسي المستعرَض. يمكن تدوير نفس التركيب بزوايا مختلفة، اي 90 درجة، 45 درجة و-45 درجة ليماثل وظيفة مضمن الاستقطاب في انظمة توزيع المفتاح الكمي. يمتلك التركيب المصمم نسبة فصل تساوي تقريبا 60000 ومدى تفاوت زاوي واسع من -20 درجة الى 20 درجة.