High-resolution Measurement of Refractive Index Based on Resonant Tunneling Effect

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Abstract. A high-resolution measurement device of refractive index with high transmissivity and Q factor based on resonant tunneling effect is presented. The device is constructed by one dimensional photonic crystal (PC) with a defect which would produce different resonant peaks in PC band gap. These peaks are sensitive to the change of the refractive index for different mediums which are filled in the defect. It is found that with a spectrometer that can resolve a resonant peak shift of 0.5nm, at the resonant wavelength of about 1550nm, the resolution of refractive index should be better than 0.0008, and the transmissivity could be accessible to 1. Both the plane wave method and the finite difference time domain method are employed in numerical analysis. The device is suitable in a variety of applications of practical interest, since many physical, chemical, and biological parameters can be known through measurement of the refractive index.

1. Introduction

Refractive index is one of the fundamental material properties, because it is closely related to the electronic polarizability of ions and the local field inside the material [1]. The accurate measuring, monitoring or sensing of refractive index is of scientific and technological importance in many cases [2]. In physics, by accurate measuring the refractive index, many physical features may be perceived, such as light spectrum structure, optical properties, purity and concentration of gas or liquid, and so on [3]. In chemical, pharmaceutical, beverage, or food industries, the monitoring of refractive index is part of the quality control. In biosensing, with the changing of refractive index, molecular bindings, chemical, or biochemical reactions are carried out continuously, thus the detection of minute refractive index changes is crucial [4]. In the fabrication of integrated optical devices, such as filters, switches and modulators, etc., where the refractive index of material is the key parameter for device design, the sensing of tiny refractive index changes is decisive for monitoring the production process.

Owing to the broad range of applications just mentioned, new measuring principles and methods of refractive index are constantly appearing. Many devices based on different principles have been proposed, such as angular surveying instrument, interferometric testing apparatus, F-P interference sensor, all-fiber interferometers or resonators, and biochemical sensors [5]. However, they have also some drawbacks. Some measuring devices, for example, have complex design with high price, are fragile, instable, or incapable of on-line monitoring. In most cases, it is difficult to reach relevant request of sensitivity, precision and measuring range simultaneously.

In this paper, we report a novel high-resolution measuring method which detects the value of refractive index based on resonant tunneling effect in photonic crystal (PC) [6, 7]. One dimensional
PC is used because there have more methods and more mature technology in its fabricating compared with two and three dimensional PC. The paper is organized as follow. Firstly, we will define our model system and describe the theoretical method. Secondly, we will try to perform the optimal design with geometric and material parameters, and the policy of design is expounded. Thirdly, numerical results will be presented together with an improved discussion. Finally, some remarks will be given. In our study, both the plane wave method [8] and the finite difference time domain method [9, 10] are used for numerical analysis.

2. Physical model and theoretical method

The schematic diagram of our test device researched in this work is composed by stacking TiO$_2$ and SiO$_2$ layers with a defect which is used to fill different materials, as shown in Figure 1. For convenience, we denote the structural configuration as $(HL)_m(D)_n(LH)_m$, where $m$ is the repeated number of the unit “$HL$”, $n$ is the periods of the unit “$D$” which represents the thickness of the defect. The refractive index and thickness of layer $H$ ($L$) are $n_H=2.2$ ($n_L=1.44$) and $d_H=0.4a$ ($d_L=0.6a$), respectively, where the parameter $a$ is the lattice constant of the PC. The layer $D$ is chosen with the same thickness as layer $H$ ($d_D=0.4a$) but different refractive index $n_D$. Obviously, one kind of PC is formed by $(HL)_m$ (marked as PC $(HL)_m$). It is not difficult to imagine that this structure is just similar to semiconductor quantum well system. The PC $(HL)_m$ can be regarded as a potential barrier for the propagation of electromagnetic waves and be utilized to quantize the continuous states of a suitably chosen quantum well material into a series of photonic bound states, much like the way potential barriers are used to quantize the electronic states of a semiconductor; while “$(D)_n$” may be thought of as potential well, whose material may be chosen according to ours needs.

In the case of the same thickness $(D)_n$ with the invariable geometric and dielectric parameters of PC $(HL)_m$, the transmission spectrum is only determined by refractive index of $n_D$. Thus we can call this device as “refractive index sensor”. The different transmission spectra with different $n_D$ are calculated based on the plane wave method and the finite difference time domain method. To minimize back reflection, the computational region is bounded by the PC-based perfectly matched layers. The parallel light originated from broadband optical source and transformed from convex lens $L_2$ is normally launched upon the surface of PC $(HL)_m$. In the design of the device, the coaxiality and the parallelization of the convex lens should be insured, so as to improve the coupling efficiency of light. The other request is that the input and output faces of PC $(HL)_m$ should have good temperature stability and should not receive effects of shearing stress, so as to insure the stability of optical property. In favor of the observation, in the calculated diagrammatic curves of transmission spectra, the Y-coordinate value is calculated as the ratio of transmitted power to the incident power; the
frequencies described in the X-coordinate are in the normalized frequencies which take \((\omega a / 2\pi c)\) as their units, \(c\) is the propagation speed of light in vacuum, and \(\omega\) is the angular frequency.

3. Numerical results

The PC \((HL)_m\) provides a photonic band gap (PBG), in which the propagation of electromagnetic (EM) waves or photons is strongly inhibited. Although there are no photon modes in the PBG, the defect modes (sharp peaks) could be induced by breaking its periodicity due to change of the interference behavior of light. Figure 2 (a) and 2(b) show the transmission spectra of \((HL)_m\) and \((HL)_3(D)_4(LH)_3\), respectively. It can be seen that defect modes would emerge in the PBG and could transmit through the well region. We interpret this phenomenon as the effect of resonant tunneling, not in a usual way. Obviously, such a PBG may be viewed as a perfect mirror and is particularly useful for constructing the resonant cavities in the optical region, and only the resonant frequencies can be captured by this cavity. We can conjecture that the resonant frequency of the sharp peaks would shift when the refractive index of defect layer \((D)_n\) changes. Therefore the change in the refractive index of the defect layer \((D)_n\) can be obtained measured by measuring the output spectrum.

It is worth mentioning that both the transmissivity and the quality factor \(Q\) are important parameters for the measurement of refractive index, which are closely related with the sensitivity and the precision. The \(Q\) factor is defined as \(\frac{\omega_0}{\Delta\omega}\), where \(\omega_0\) is the center frequency of the defect modes, and \(\Delta\omega\) is half-height width of the resonance peak. The higher the transmissivity is, the lower energy loss is, the lower the temperature rise is, and thus the simpler the instrument's maintenance is. The larger the \(Q\) factor, the higher the sensitivity can be achieved. Figure 3 show the transmission spectra of \((HL)_n(D)_m(LH)_n\) with the same \(n=4\) but different \(m=4, 8, 10\), respectively. These results demonstrate that, with the increasing of the thickness of PC \((HL)_n\), the \(Q\) factor is increased, but the transmissivity is reduced. It can be explain that, the wider the thickness of \((HL)_n\) is, the stronger the reflection is, and therefore the lower the transmissivity is; simultaneously, the less the overlapping of wave functions is, the weaker the coupling effect between the input and output PC is, the stronger the filterability of this device is, the sharper the resonant peaks is, and thus the higher \(Q\) factor is. From the above discussions, we should suitably choose the value of \(m\). In our next design, \(m=8, n=4\) are chosen with a transmissivity of more than 0.9 and a \(Q\) factor of more than 750.

![Figure 2. Transmission spectra for (a) PC \((HL)_m\) (b) \((HL)_3(D)_4(LH)_3\)](image)
Figure 4 shows the transmission spectra for different refractive indexes in an increment of $\Delta n = 0.0008$. Please noted that the refractive index of the middle spectrum (labeled the mark of “*”) is $n_D = 2.2$. While the refractive index increases, the resonance hump shifts toward left, i.e., red shift. The expression of refractive index $n_D$ can be expressed as $n_D = 2.2 + p \times 0.0008$ ($p = \pm 1, \pm 2, \pm 3, \cdots$), where $p$ is the number offset away from the middle spectrum for researched resonance hump; while the researched resonance hump is on the left of the middle spectrum, $p$ takes the sign of “+”; on the contrary, takes the sign of “-”. It is not difficult to see there is direct proportion relation between the normalized frequency of the resonance hump and the refractive index $n_D$, and the normalized frequency between two neighboring resonance peaks is about 0.00006. According to the relation: 

$$\Delta \lambda = (\Delta \omega \cdot \lambda_0^2)/c,$$

where $\lambda_0$ is the center wavelength of resonance peak, $\Delta \omega$ is frequency change value, and $\Delta \lambda$ is wavelength change corresponding to $\Delta \omega$. From the above relation, in the case of $\lambda_0 = 1550$, it can be obtained that the resonant wavelength shifts 0.5nm with $\Delta n = 0.0008$ (corresponding to normalized frequency $\Delta \omega = 0.00006$). Because of the high Q factor, the full width at half-maximum is only approximately 0.48nm, thus the peak values of the spectra can be clearly resolved and the measurement accuracy is assured. As a result, a relative measurement error is less than 0.5%.

4. Conclusion

We have presented a measurement device of refractive index with high transmissivity and Q factor based on resonant tunneling effect. Our device is constructed by one dimensional PC with a defect which gives rise to different resonant peaks in PC band gap. These peaks are sensitive to the medium which is filled in the defect. One of the features that make the device proposed here is the fact that all the peaks can be used simultaneously to monitor the refractive index with high resolution. With a spectrometer that can resolve a resonant peak shift of 0.5nm, at the resonant wavelength of about 1550nm, the resolution of refractive index should be better than $\Delta n = 0.0008$, and the transmissivity could be accessible to 1. The device is suitable in a variety of applications of practical interest, since many physical, chemical, and biological parameters can be known through measurement of the refractive index. In addition, this device is compact, robust, and highly stable over time, and thus can be widely applied in the fields of optical sensor and integrated optics.

Acknowledgement. This work was supported by the Scientific Research Program of Education Bureau of Hunan Province (08C368) and Hunan Provincial Natural Science Foundation of China (10JJ6095).
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