Study on hollow-core photonic crystal fiber terahertz evanescent wave sensor in drug detection

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In order to find an efficient way in drug detection, a new measurement that based on the hollow-core photonic crystal fiber of terahertz (THz-PCF) evanescent wave sensor is proposed by the plane wave method (PWM) and the finite element method (FEM). Through constantly changing the size of the air hole and adjusting the distance between each hole to find out the optimum state. Results reveal that when the diameter of air hole is 92um and the distance between each hole is 100um, the THz wave can spread much more smoothly in PCF. Furthermore , when the confinement loss of hollow-core THz-PCF evanescent wave sensor is 0.18 dB/m, the relative sensitivity can reach 98.8561%. Therefore, the hollow-core THz-PCF evanescent wave sensor has good advantages in drug detection.

(Received February 16, 2013; accepted September 18, 2013)

Keywords: THz, PCF, Evanescent wave, Drug, Relative sensitivity

1. Introduction

It is well-known that the drugs have done harm to many families every year, so to prevent the drugs smuggled and trafficked has been an emergency. At present, the main and effective way to detect drug are police dog and X-ray in the customs. However, they still have some disadvantages that the police dog can be useful only when there have some scattered substances outside, and the X-ray cannot determine the type of drug and have radiation hazard to human body. Nowadays, the target to search a new way has attracted great attention of researchers. Various fundamental researches have been done in the laboratory, such as chemical chromogenic method, chromatography method [1] and terahertz time-domain spectroscopy. But they are inefficient and destructive and the equipment of detection is complex [2]. THz wave is an electromagnetic wave that its frequency is between 0.1 THz and 10 THz. The overlap part of long wavelength and millimeter wave becomes the link of macroscopic electronics and microscopic photonics for its special position. In the frequency range of THz wave, many drugs have absorption peak, such as methamphetamine (MA), ecstasy (methylene two oxygen base Benzedrine MDA), etc. Low frequency vibration in THz band and low THz energy determine it is not easy to damage the detected material [3]. All above demonstrate THz wave is a promising candidate for drug detection.

The concept of PCF was proposed by ST. J. Russle etal in 1992 [4]. The first index guide PCF is developed in 1996 [5] and the first band gap of PCF is manufactured in 1998 [6]. The hollow-core band gap PCF has many advantages, such as easy coupling, without Fresnel reflection, low bending loss, low nonlinear and special waveguide dispersion characteristics. Thus it has been widely use in high power light, optical fiber sensor and gas optical fiber, etc. British Bath researchers developed a hollow-core PCF whose transmission wavelength could cover to near infrared band in 2002 [7]. And in 2011, Haixia Cui studied the basic sensitivity of evanescent wave about PCF to THz wave, but its sensitivity is not high. On the basis of them, THz-PCF is applid to probe drugs and form the absorption peak library to find out the matchable one. And results show the study to detect drug with THz-PCF evanescent wave sensor by PWM and FEM is significative.

2. The principle of THz-PCF evanescent wave sensor

The principle of THz-PCF evanescent wave sensor is combining the light source with the plastic THz-PCF, making the evanescent wave which leaked into the hole interact with the materials whose absorption spectrum in THz wave. The type and concentration of under test material are settled down by the output light intensity change of evanescent wave. In total internal reflection (TIR) PCF, only a small part of the evanescent wave absorbed by the material, most of the light transmit in the core. According to D' alembert's principle, the relationship between light energy density and concentration of the under test material is:

$$I(\lambda) = I_0(\lambda)\exp[-r\alpha(\lambda)lC] \quad (1)$$

I and I_0 denote the power density of output and input light relatively; $\alpha(\lambda)$ is the absorption coefficient of under measured material; l is the length of probe which based on PCF; C is the concentration of the under measured material; r is the relative sensitivity coefficient and has been defined as follow:

$$r = (n_r/n_e)f \quad (2)$$

n_r represents the effective refractive index of the under measured object; n_e is the effective refractive index of fundamental mode. After the mode is determined, the f is the ratio of light energy and the total energy in the air hole, according to poynting's vector:

$$f = \frac{\int_{holes}(ExHy - EyHx)dxdy}{\int_{total}(ExHy - EyHx)dxdy} \quad (3)$$

The Ex, Ey, Hx, Hy represent the x, y component of transverse electric and magnetic fields[8].

3. Numerical simulation and analysis of results

3.1 Band gap analysis

The THz-PCF evanescent wave sensors is analyzed by PWM and FEM. PWM divides the electromagnetic into a periodic function and a plane wave by the Bloch theorem, at last transform the Maxwell equation into an intrinsic equation for getting the intrinsic value and frequency. The FEM is an algorithm that can solve mathematics and physics problems based on variational principle. The distribution problems of PCF mode that composed by any irregular section shape and refractive index can be solved well by software of COMSOL. Polymethylmethacrylate (PMMA), known as organic glass, is chosen as the material of PCF. It has many advantages, such as the most excellent transparent polymer, low price, easy to machining and so on. The refractive index of PMMA is 1.6. In order to restrict the light transmission frequency range around 1.4 THz, through continuous change the diameter of air holes and distance between the holes, the most appropriate diameter of the air holes of PCF is 92 um, and the distance of each hole is 100 um, as shown in Fig.1. Band gap range has changed constant normalized propagation, which is shown in Fig. 2. The straight line means the air line, the overlap part is band gap range of PCF. It demonstrates that the band gap range is between 2.8 and 3.18, the translated frequency range from 1.337 to 1.519 THz. The THz frequency range is needed.

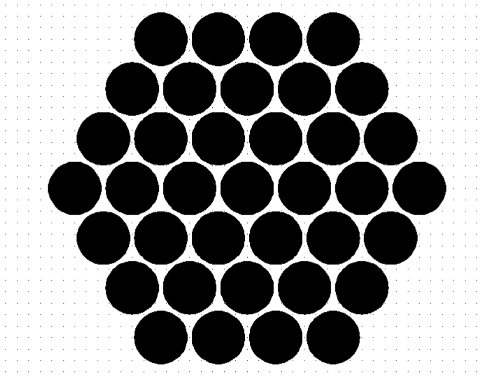

Fig.1 Cross section of PFC.

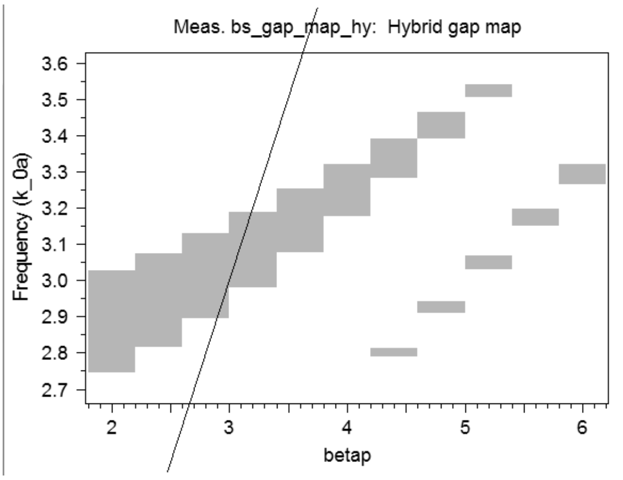

Fig. 2 Frequency constant normalized propagation

According to the reports, a lot of drugs have their absorption peaks in the THz band. For example, the MA are 1.2 THz and 1.7-1 .8 THz, the MDA are 1.4 THz and 1.8 THz. MDA is used to analog and simulation, get a refraction index of 1.4211, the filler in center hole of PCF in Fig.1 is MDA. In order to verify that the designed PCF can detect drugs effectively, software of Rsoft and COMSOL are used to analog and simulation. When simulated, the frequency of THz is settled as 1.5 THz. Fig.3 is the amplitude curves of THz wave just enter into PCF and Fig.4 is the amplitude of THz after transformed 8 mm. In the process of transmission, almost all the energy can be concentrated well in the fiber core. Then, simulating the energy propagated in the core by software COMSOL, as shown in Fig.5. Through the result indicated that the designed PCF can be used for the detection of drugs.

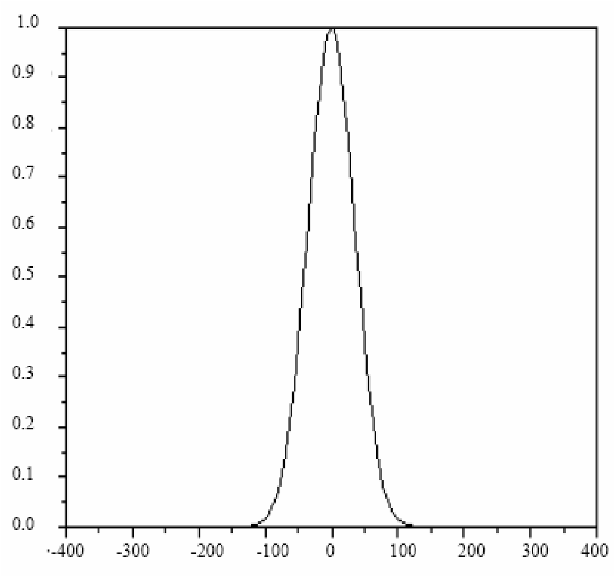

Fig.3 Amplitude at the entrance of PCF

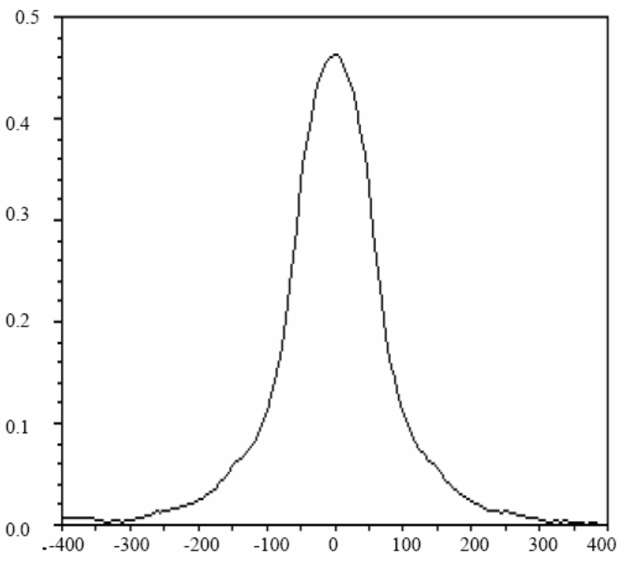

Fig.4 Amplitude of light after spread 8 mm in PCF

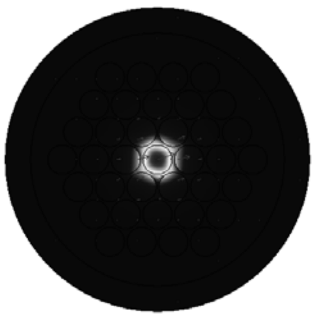

Fig.5 The fundamental core mode on 1.5 THz

3.2 Sensitivity analysis

The reason of selecting hollow-core PCF to detect drug is that its relative sensitivity is much higher than solid one. In the premise of the same structure parameters of hollow-core PCF and solid-core PCF, the relative sensitivity of the two PCF was analysed by using COMSOL. The effective refractive index of the fundamental mode of a solid-core and a hollow-core PCF changed with the frequency is shown in Fig.6. It's obvious that the effective refractive index both increased when the frequency improve. Nonetheless, the effective refractive index of fundamental mode of the hollow-core PCF is much smaller than the solid. Fig.7 is the relationship between relative sensitivity of the solid-core and the hollow-core PCF changing with frequency. It can be seen that the lowest relative sensitivity of the hollow-core PCF is 94.0138%, the highest is 98.8561%, having increased about 54% compared to the maximum of solid PCF (44.4388%). The relative sensitivity of designed hollow-core PCF has greatly improvement comparing with other evanescent wave sensor, which provides a good theoretical basis for THz-PCF evanescent wave sensor used in drugs testing.

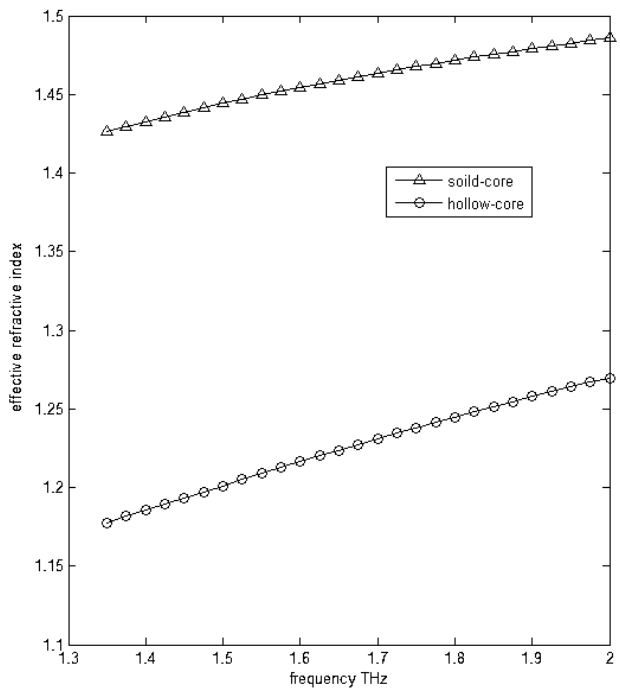

Fig.6 Shows effective refractive index constant at different frequency.

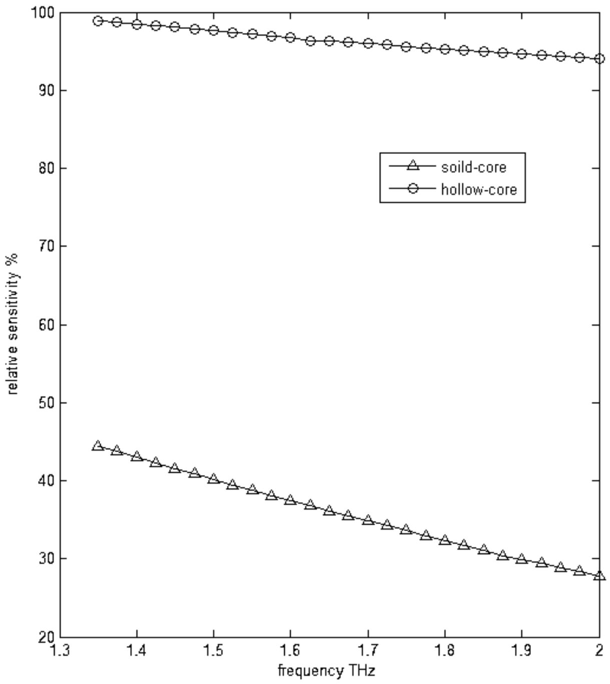

Fig. 7. Shows relative sensitivity constant at different frequency

The sensitivity and the confinement loss should be considered when analysing the sensitivity of evanescent wave. If improve the sensitivity in the premise of increasing limit loss, the application is also undesirable even if the sensitivity has be improved. Fig.8 and Fig.9 is the confinement loss of a solid-core and hollow-core PCF changing with frequency. The confinement loss of the solid-core PCF is restricted at the orders-of-magnitude of 10^{-5}, and the hollow-core PCF also can be decreased to 0.18 dB/m. Although confinement loss of solid-core PCF is much smaller than hollow-core, the relative sensitivity of the hollow-core PCF can reach to 98.8561%. This confinement loss is small enough to meet the needs of detection.

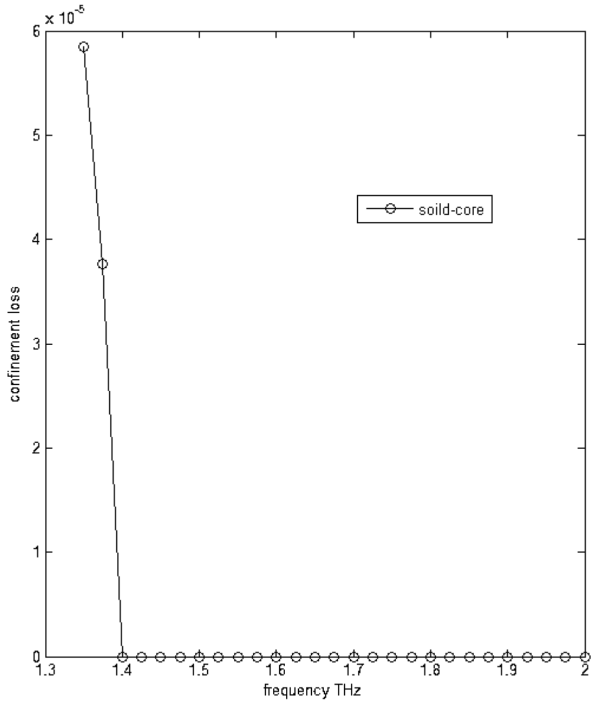

Fig.8 The confinement loss of solid-core THz-PCF constant at different frequency

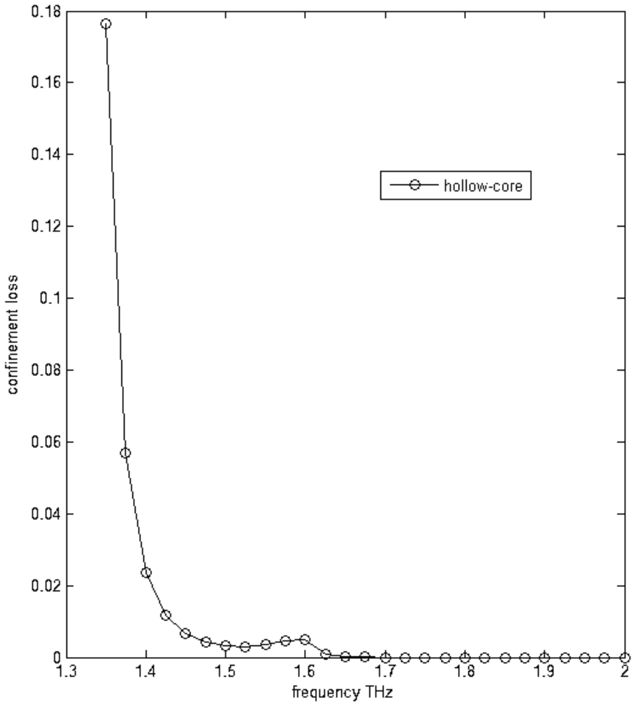

Fig.9 The confinement loss of hollow-core THz-PCF constant at different frequency

4. Conclusion

To draw a conclusion,the performance of the hollow-core THz-PCF evanescent wave sensor used for drug detection was done. Firstly, find a most appropriate structure which the diameter of the air holes of PCF is 92um and the distance of each hole is 100um to spread by PWM. Then analyze the relative sensitivity and confinement loss by FEM. The highest sensitivity of hollow-core PCF can reach 98.8561%, while only 44.4388% for solid-core to further demonstrate the superiority of this structure. What's important, the relative sensitivity of the hollow-core PCF has been greatly improved compared to the solid-core PCF in the same structural parameters. Therefore, it is feasible use evanescent wave sensor of hollow-core PCF to detect drugs, and this work provides an important theoretical foundation for a convenient, effective, non-destructive drugs testing.

Acknowledgments

This research was supported in part by the China Postdoctoral Science Foundation (Grant No. 20090460691), the National Basic Research Program of China (Grant No. 9732010CB327801).

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