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A novel plus shaped cavity based optical fiber sensor for the detection of Escherichia-Coli

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ABSTRACT

In this work, we have demonstrated the refractive index (RI) based sensing of Escherichia Coli (E-Coli) by introducing a novel plus shaped cavity in optical fiber. This plus-shaped cavity increases the interaction between the signal and the analytes, that improves the sensitivity. The proposed sensor model is achieved by combining the lateral and vertical slots in optical fiber core structure. The sensing ability of the plus shaped cavity has been examined in visible range, where the RI of E-Coli ranges from 1.38 to 1.395. The numerical investigation of sensor structure has been done by employing the finite difference time domain (FDTD) method. The geometrical analysis of plus shaped cavity indicates that; the maximum output power is achieved at the slot width of 600 nm. The proposed cavity is capable of sensing the presence of E-Coli with the autocorrelation function and sensitivity of 99.54 % and 2125 nm/RIU, respectively.

1. Introduction

The most common pathogenic agent for food-borne diseases is Escherichia Coli (E-Coli) (Tauxe, 2002). From the last decade, pathogenic agent-based diseases are among the primary concerns across the world (Flint et al., 2005; Ashbolt, 2004). The regular intake of infected food or water can be deadly, especially for children and elderly population. The 2015 report of World Health Organization (WHO) states that 40 % of the 33 million population of the children less than five years are suffering from E-Coli infection (Havelaar et al., 2015). The E-Coli pathogens are associated with high illness and death rates (Altekruse et al., 1997). Therefore, the detection of E-Coli is crucial to control its outbreak. The PCR, ELISA and IMS are some recent techniques that have been used for rapid E-Coli detection, but still facing challenges in terms of complicated sample pretreatment, time consumption, trained operators and expensive process (Bonetta et al., 2016; Zhao et al., 2018). Therefore, researchers proposed several techniques for rapid and sensitive diagnosis of food or water testing processes such as evanescent wave based grating couplers (Horváth et al., 2003), optical transmission based waveguides (Zourob et al., 2005), surface plasmon resonance (SPR) biosensors (Irudayaraj and DebRoy, 2007) and surface enhanced Raman spectroscopy (SERS) (Srivastava et al., 2015). Among these, SPR sensors have received much attention because of higher sensitivity which is primary requirement in bio-measurement (Bae et al., 2004; Choi et al., 2008; Janz et al., 2013; Gupta et al., 2018). In last decade, different SPR optical fiber grating structures were reported for the monitoring of diseases and the environment such as long period fiber grating (LPFG) (Kaushik et al., 2016; Queirós et al., 2014) and fiber Bragg gratings (FBG) (Tiwari and Kaushik, 2017; Srinivasan et al., 2017). The sensitivity of SPR sensors was improved by using nanomaterial based surface modification, and have been used in biological sensing (Kant et al., 2017; Nayak et al., 2017; Usha and Gupta, 2018). Optical fiber SPR sensor have also been used in refractive index (RI) based measurement (Shrivastav et al., 2015; Tabassum and Gupta, 2015; Mishra et al., 2014). Despite of remarkable properties, SPR sensors also suffers with numerous limitations such as bulky movable components and losses due to input fluctuations or connection issues (Bae et al., 2004). Therefore, to overcome the above mentioned drawbacks grating based sensors were comes into picture (Smietana et al., 2011). However, the physical adsorption and low sensitivity of the sensor limits their use for the lower concentration of analytes. LPFG based E-Coli sensor was reported with higher sensitivity and label free detection (Tripathi et al., 2012). Likewise, different geometries were proposed to enhance the sensitivity of sensors. For instance, a V-shaped LPG sensor was developed for the RI based sensing of bending vectors with effective dip in wavelength shift and higher sensitivity (Zhang et al., 2018). In another

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work, a D-shaped FBG sensor structure was used for measuring the RI of liquids such as acetone, methyl alcohol, isopropanol, alcohol and water (Chen et al., 2007). The main motivation behind the creation of different structures of cavity is to improve the field distribution and to attain effective modulation that can produce better and precise results for RI sensing.

In this work, for the first time we have introduced a plus shaped cavity based optical fiber sensor for the RI based detection of E-Coli. A step-wise process has been used for the modelling of plus shaped cavity based sensor structure. Firstly, the parameter optimization was done by analyzing the linear fiber core structure. Then, vertical and lateral slot structures were individually analyzed in the presence of E-Coli RI. Finally, the vertical and lateral slots were combined together to cascade the plus shaped cavity. The sensing ability of sensor was analyzed in presence of a wide range of E-Coli RI from 1.384 to 1.395. The numerical investigation of all the geometries was done by using finite difference time domain (FDTD) method. The manuscript is divided into five sections. The introductory part is covered in the Section I. Section II, presents the modelling of plus shaped cavity structure. The obtained results and their analysis is briefly discussed in Section III. A comparative analysis of present work with existing sensor models is presented in Section IV. Finally, the conclusion and future aspects of the work are discussed in Section V.

2. Modelling of plus shaped cavity based optical fiber sensor structure

Firstly, 8 μm long linear fiber core structure with a width of 1.125 μm was considered to model the plus shape cavity as shown in Fig. 1. Thereafter, 1 μm wide vertical and lateral slots were created in linear core as shown in Fig. 2. The RI distribution profile of both the slots is also presented in the inset of Fig. 2. The forward and backward propagating mode fields in single slots can be evaluated by using coupled mode theory (CMT). The CMT is applicable for single chromatic frequency or continuous wave (CW) input source particularly for the linear propagation of fields (Christiansen et al., 2000). However, for discrete signal the fields can be evaluated by considering individual component over the complete range of spectrum. Finally, plus shaped cavity was modelled by combining vertical and lateral slots in the center of linear fiber core as presented in Fig. 3. The RI distribution profile of plus shaped cavity is also presented in the inset of Fig. 3.

3. Results and discussion

Modelling of all the geometries was done under the meshing of 0.15 × 0.15 μm in both x and z directions. An input power of 0.1 W/μm was used with transverse magnetic (TM) polarization under the contour of perfect matched layer (PML) as boundary conditions. The linewidth and wavelength of input source were set to 0.41 μm and 590 nm, respectively. The sensing analysis of plus shaped cavity was done in presence of E-Coli RI ranging from 1.384 to 1.395 (Balaev, 2002).

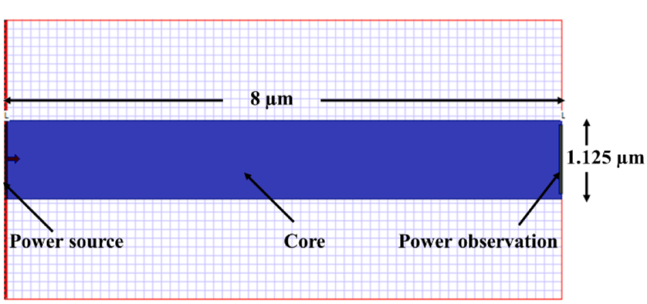

Fig. 1. Layout of linear fiber core structure.

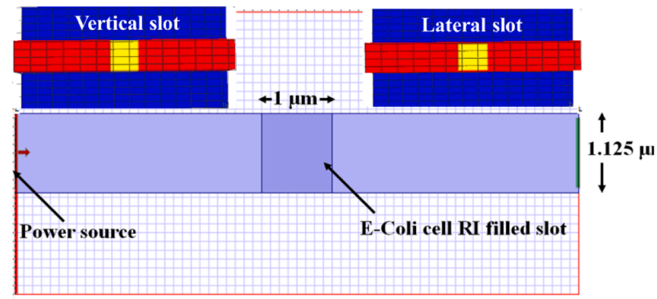

Fig. 2. Layout of vertical slot grating structure with RI distribution profiles.

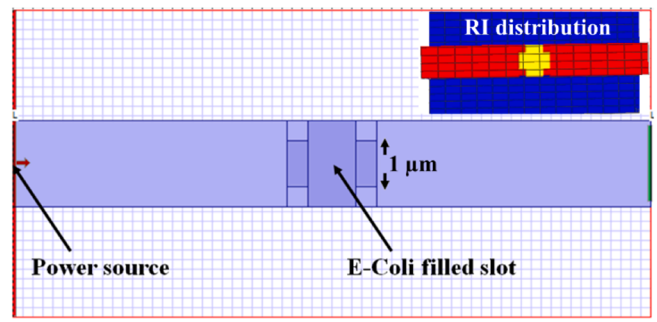

Fig. 3. Layout of plus shaped cavity structure with its RI distribution profile.

3.1. Linear fiber core structure

The analysis of linear fiber core structure was done for optimizing the parameters. The analysis was carried out in terms of optical power confinement, incidence angle and line width. The attained results are presented in Fig. 4. The confinement of real and imaginary parts of field along the perpendicular directions are presented in Fig. 4(a) and (b), respectively. From the results, it was concluded that the power is deeply confined in the core. The discrete power distribution along the lateral length of core is given in Fig. 4(c), which states that the maximum power is confined with equal distribution in perpendicular directions. Afterwards, the analysis was done to examine the impact of incidence angle on output power and results are presented in Fig. 4(d). In practice, optical connectors are available to launch the optical signals. But, in present work, we have used a fiber core of different diameter. From the results, it was observed that maximum output power attained at the incidence angle of 3.5^0. Similarly, the impact of linewidth on output power was inspected by varying it from 0.34 μm to 0.46 μm. The trend in Fig. 4(e) states that, maximum output power attained on the linewidth of 0.41 μm which is about 9.31 × e-3 W/μm.

3.2. Single vertical and lateral slots

The optimized parameters of linear fiber core structure have been used to analyze the single vertical and lateral slots. Firstly, 1 μm wide vertical slot was created in center of the core. The RI of slot was set to 1.395 which corresponds to the RI of E = Coli at 589 nm (Bryant et al., 1969). Then, the analysis was done in terms of power distribution and confinement as illustrated in Fig. 5. The geometrical representation of real and imaginary parts of the propagating fields is presented in Fig. 5 (a) and (b), respectively. The attained results states that both component of the fields are deeply confined along the transverse axis. The representation of field confinement along the propagation direction is presented in Fig. 5(c). From the results, it was conceived that field components are repeating themselves by obeying the phenomenon of total internal reflection. The distribution of fields along the core is presented in Fig. 5(d), which depicts that the optical field loses its

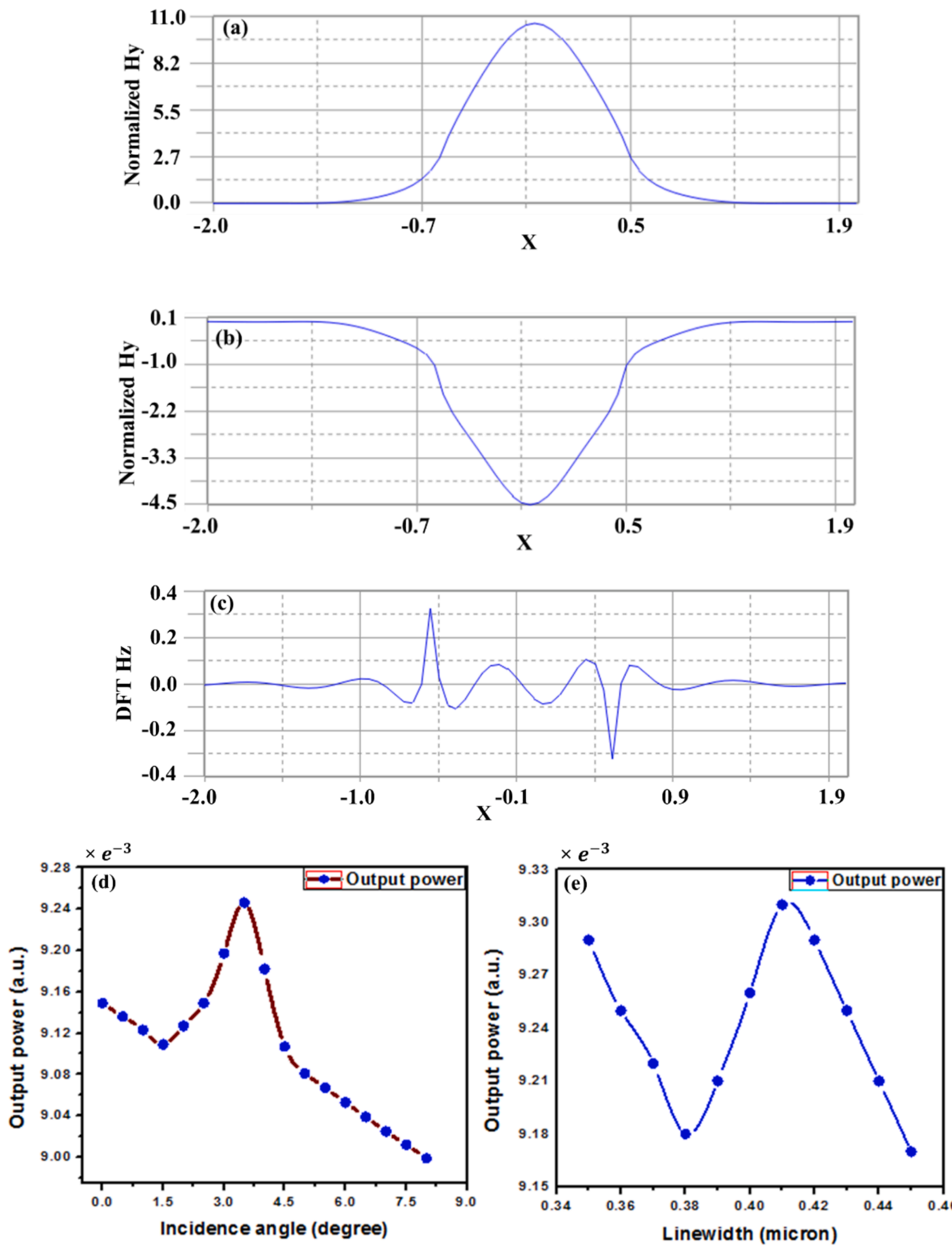

Fig. 4. Results of linear fiber core structure. Power confinement: (a) Real part, (b) imaginary part, (c) Hz component, (d) along the fiber core. Output power: (d) incidence angle and (e) linewidth.

amplitude in vertical slot due to the presence of E-Coli RI. The presence of E-Coli absorbs the signal power that results in its power and amplitude loss, which has been used to evaluate the sensitivity of sensor structure. The analysis of both the single slot structures was done in terms of impact of their widths on output power. The trends of obtained results for vertical and lateral slots are presented in Fig. 6(a) and (b), respectively. From the results, it was observed that for both the single slots maximum output power is achieved at the widths of 400 nm. However, the response of both the slots is different for the variety of slot widths. For the slot width of less than 100 nm, variation in output power is almost negligible. Therefore, for analyzing the plus shaped cavity the slot widths of 400 nm were considered.

3.3. Plus-shaped cavity sensor

The optimized simulation and geometrical parameters of linear core and single slot structures were used for cascading and analyzing the plus shaped cavity structure. The analysis of E-Coli RI filled cavity was done in terms of signal behavior, incidence angle and slot widths. The signal propagation throughout the fiber is presented in Fig. 7(a). The results indicate that, signal is deeply confined within the core with an amplitude dip in plus cavity which is because of the presence of E-Coli RI. Whereas, towards output end of core the signal is propagating with higher amplitude due to higher RI and change in its internal properties. The discrete distribution of signal confinement in perpendicular

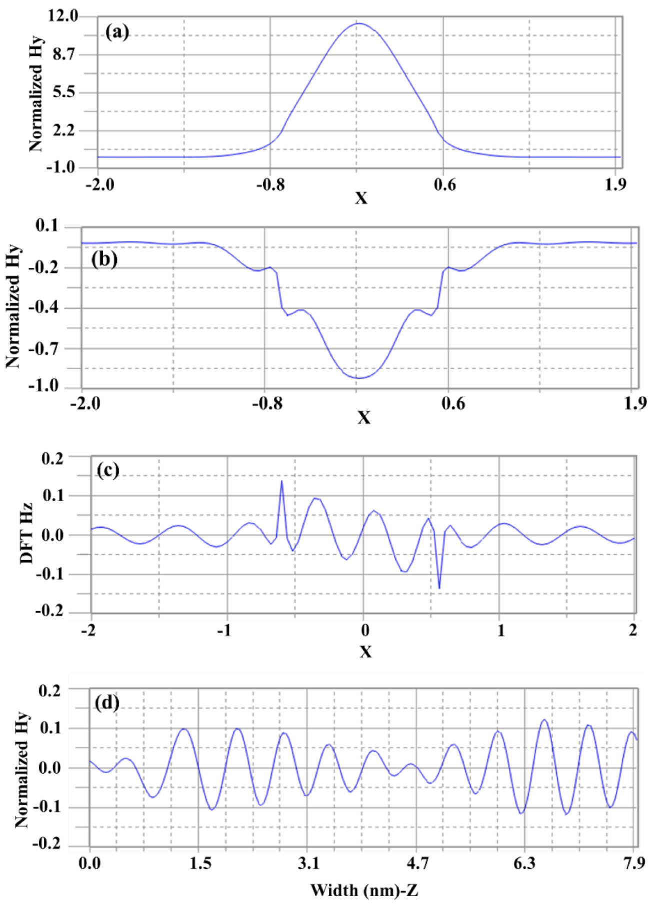

Fig. 5. Analysis of single vertical slot. Field confinement: (a) real part, (b) imaginary part, (c) transverse to propagation direction, and (d) along the propagation directions.

direction is given in Fig. 7(b). From the results, it was observed that signal amplitude varied in center and sharply confined towards the cladding. Afterward, the analysis of cavity was done by observing the impact of incidence angle and slot widths on output power and obtained results are presented in Fig. 8(a) and 8(b), respectively. The trend shown in Fig. 8(a) depicts that, the output power is linearly increasing with incidence angle till 3.5^0, which was used for analyzing the sensing ability of cavity. Similarly, the impact of slot width was analyzed by varying their widths from 50 nm to 1000 nm as shown in Fig. 8(b). The maximum output power was attained at the slot widths of 600 nm. Thereafter, the sensing ability of sensor model was analyzed in presence of E-Coli RI ranging from 1.384 to 1.395. The trend of output power to RI is presented in Fig. 9(a) which states that output power is proportionally increasing with RI. The autocorrelation curve of sensor is presented in Fig. 9(b), from where it was concluded that proposed sensor model is capable of sensing the E-Coli RI in tested range with sensitivity and autocorrelation coefficient of 2125.5 nm/RIU and 99. 54 %, respectively.

4. Specificity of the proposed sensor

The specificity is an important factor to analyze the performance of any sensor The analysis of specificity of proposed plus shaped cavity sensor is investigated by including a layer of E-Coli 0157:H7 antibody around the cavity. Then, the specificity is measured by performing the RI based detection of Salmonella Typhimurium (ST) and Shigella Flexneri (SF). The Salmonella Typhimurium and Shigella Flexneri are the bacteria which are observed at the substrate RI of 1.43 and 1.410, respectively (Bahadoran et al., 2016; Liu, 2016).

The analysis was done by measuring the variation of output power in presence of RI of different tested analytes and the obtained results are presented in Fig. 10. From the results, it can be observed that the output power for E-Coli is higher at the operating wavelength of 615 nm that is about $9.178 \times e^{-3}$ W/μm. Whereas, the output power for other analytes such as Salmonella Typhimurium (ST) and Shigella Flexneri (SF) is low that is due to the presence of EC antibody RI.

5. Comparative analysis

The validation of proposed plus shaped cavity based sensor model was done by comparing its output with reported E-Coli sensor. The comparative analysis was done in terms of attained sensitivity and autocorrelation function as shown in Table 1. LPG based stable and label free biosensor has been proposed for E-Coli detection (Tripathi et al., 2012). The proposed sensor model is worked on bacteriophage based detection with accurate measurements and sensitivity of 2321 nm/RIU has been attained. Whereas, there was no discussion about the attained value of autocorrelation function. The fiber optic surface plasmon resonance based E-Coli sensor structure has been reported (Zhou et al., 2018). The sensor model provides sensitive detection of E-Coli with a regression coefficient of 99.2 %, but there was no discussion about the attained sensitivity. An evanescent wave absorbance based E-Coli sensor has been proposed for the detection of E-Coli pathogens (Bharadwaj et al., 2011). The sensor probe was developed in U-shape by bending the optical fiber at the radius of 0.75 nm. The attained results were quite interesting for pathogen sensing but there was no discussion about sensitivity and autocorrelation coefficient. A fiber optic SPR immune-

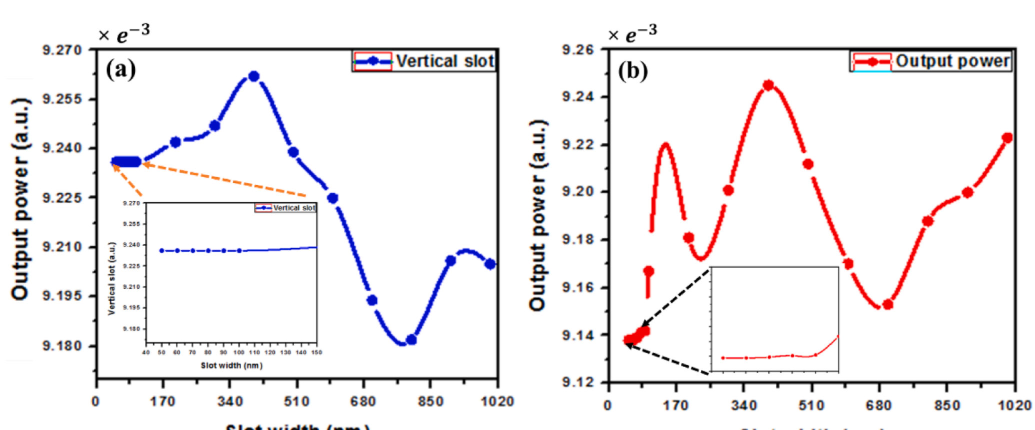

Fig. 6. Analysis of slot width versus output power: (a) vertical slot, and (b) lateral slot.

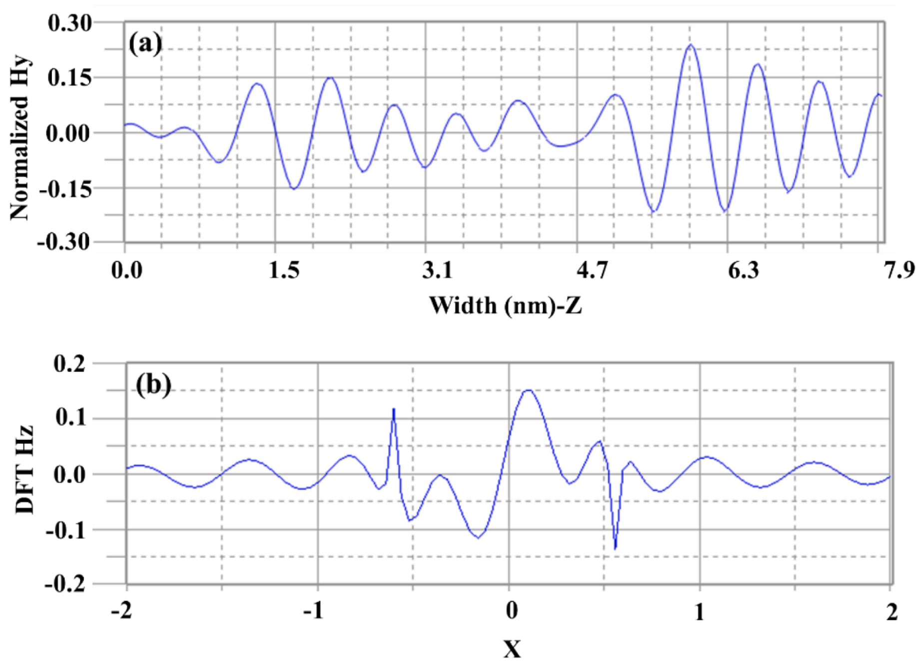

Fig. 7. Analysis of plus shaped cavity: (a) propagation of optical signal, and (b) discrete distribution of signal in perpendicular direction.

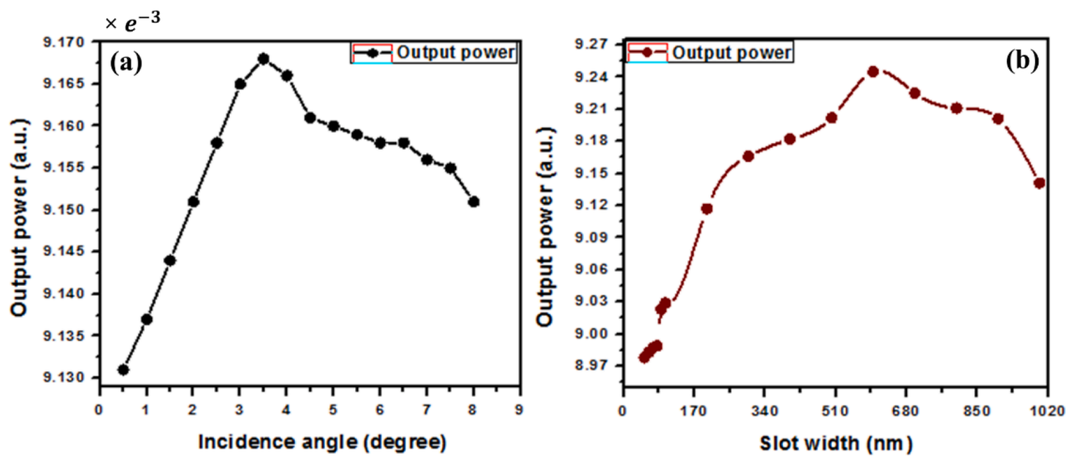

Fig. 8. Output power of plus shaped cavity with respect to: (a) incidence angle, and (b) slot widths.

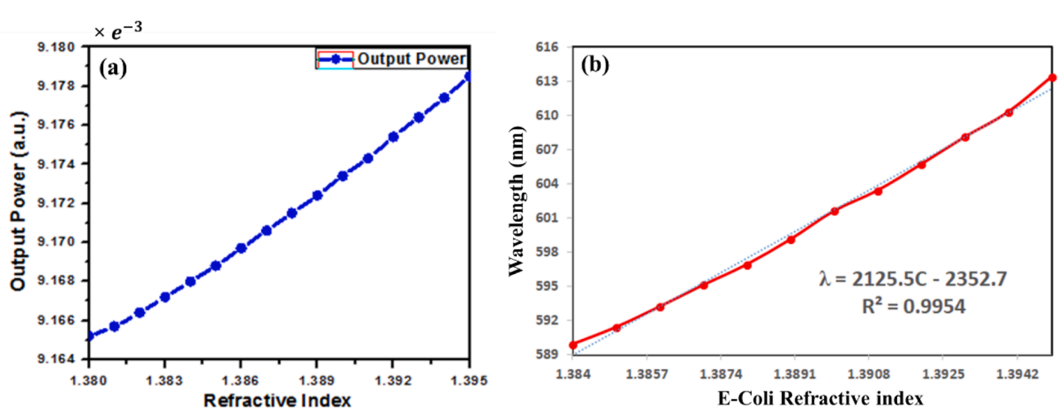

Fig. 9. Sensing analysis of plus shaped cavity: (a) RI versus output power, and (b) autocorrelation curve.

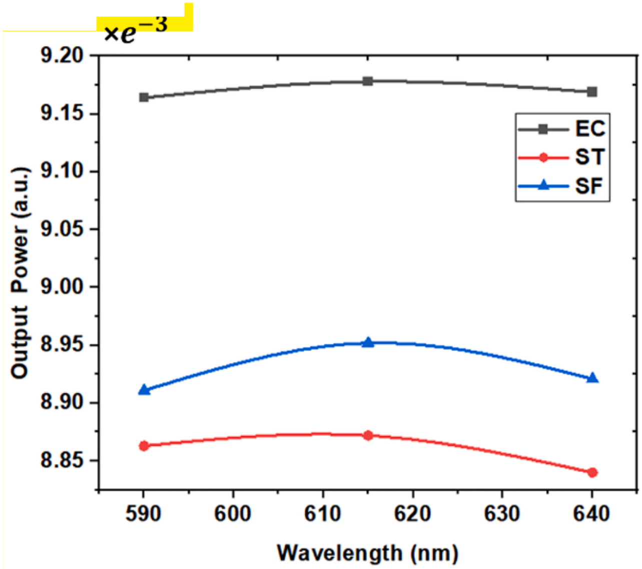

Fig. 10. Analysis of specificity of the proposed plus shaped cavity sensor.

Table 1
Comparative analysis of plus shaped cavity sensor model with reported E-Coli sensors.

Sensor structure	Sensitivity (nm/RIU)	Autocorrelation Function	References
LPG	2321	n.r.*	(Tripathi et al., 2012)
Au functionalized linear optical fiber	n.r.*	99.2 %	(Zhou et al., 2018)
U-shaped fiber	n.r.*	n.r.*	(Bharadwaj et al., 2011)
MoS_2 functionalized linear optical fiber	3135	99.4 %	(Kaushik et al., 2019)
Borosilicate optical fiber	640	66.19	(Maas et al., 2018)
Linear optical fiber	n.r.*	99.48 %	(Yildirim et al., 2014)
Plus shaped cavity based fiber	2125	99.54 %	This Work

n.r.* - not reported.

sensor based on bio functionalized Molybdenum disulfide was reported (Kaushik et al., 2019). The wavelength interrogation mechanism was used to analyze the sensor model and a linear relationship of 99.4 % was achieved. The sensitivity of 3135 nm/RIU was attained for the tested E-Coli colony of 2.9/1000 CFU ml^{-1}. A borosilicate glass optical fiber based E-Coli sensor was reported (Maas et al., 2018). The reported sensor model was sensing the presence of E-Coli based on RI variation and as a result the autocorrelation function and sensitivity of 66. 19 % and 640 nm/RIU was achieved. An aptamer based linear optical fiber structure was reported for the detection of E-Coli (Yildirim et al., 2014). The reported sensor structure works on the principal of competitive mode detection. For the detected concentration range of E-Coli, the linear fitting ratio of 99.48 % was achieved. In presented work, for the first time we have introduced a plus shaped cavity within the optical fiber core for the RI based sensing of E-Coli. The attained sensitivity and autocorrelation function of sensor are 2125 nm/RIU and 99.54 %, respectively

6. Conclusions

In summary, the present work provides a plus shaped cavity based optical fiber sensor for the detection of E-Coli. The work demonstrates the step wise analysis of sensor model. Firstly, a linear optical fiber core structure has been analyzed to optimize the parameters. Thereafter, single vertical and lateral slots were included in linear fiber core and analyzed with the optimized parameters. The analyzed results states that, for the used core structure maximum output is attained at the incidence angle and linewidth of 3.50 and 0.41 μm, respectively. Afterward, the analysis of plus shaped cavity has been done and maximum output power was attained at the slot widths of 600 nm. The sensing capability of plus shaped cavity was done in presence of E-Coli RI ranging from 1.384 to 1.395. The obtained results show that the proposed sensor model is highly sensitive for the detection of E-Coli with a maximum sensitivity of 2135 nm/RIU. The autocorrelation coefficient function of sensor model for the tested range of E-Coli RI was 99.54 %. The higher sensitivity was due to the increase in surface area between analytes and optical signal. The proposed plus shaped cavity sensor structure could be also used for the detection of single cells of E-Coli having dimensions in the range of ∼ 1 μm. An another salient feature of proposed sensor model is that it can limits the creation of number of gratings. Therefore, the plus shaped sensor model structure is point of interest for the development of optical fiber based biosensors.

CRediT authorship contribution statement

Lokendra Singh:,Gaurav Kumar:,Siddharth Jain:,Brajesh Kumar Kaushik:.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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