Realisation of white LED using fiber based hybrid photonic structures

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The generation of signal of white LED is realised in this research with the help of hybrid photonic structure, where hybrid structure deals with the combination of four plasmonic based photonic crystal fiber. Here the four square lattice photonic crystal fibers are designed in such way that first three fibers produce red, blue and green signals and fourth one will combine all three signals (R-B-G), which gives the signal of white LED. The principle of generation of these signals relies on the field distribution in the proposed photonic crystal fiber and filtering application. Aside these, different transmission spectrum are shown for the sake of confirmation of the generation of R-B-G as well as white signal. The simulation results are carried out with the help of plane wave expansion techniques. Moreover the present research indicates the throughput efficiency of each fiber though numerical expression. It is also obtained that the fiber 1, 2, 3 and 4 transmits signal (bandwidth) of 79.2 THz, 46.6 THz, 80.85 THz, and 180.8 THz corresponding to the channel capacity of 80 THz, 47.1 THz, 81.3 THz, and 182.6 THz respectively. The overall efficiency of the fiber is more than 99%. Finally, it is envisaged that the proposed hybrid photonic crystal fiber system is an equivalent to the white LED, because the proposed system generates the signal of 395 nm to 520 nm which is the spectrum of white LED.

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1. Introduction

The Light emitting diode (LED) is a fundamental component in an optoelectronic system. Basically semiconductor material based devices produce light from electricity [1-3]. The LEDs produce different colours. Moreover different types of LEDs with respect to different colours have been realised, for example, red colour LED, produces red signals (R), blue LED generates blue light (B) where green LED produces green signal (G) and similarly others. However the understanding of white LED can be envisaged through the combination of red, blue and green LEDs [4-7]. To realise the same in better ways, Fig. 1(a) shows the signal of the white light which is an intersection or combination of red, blue and green signal.

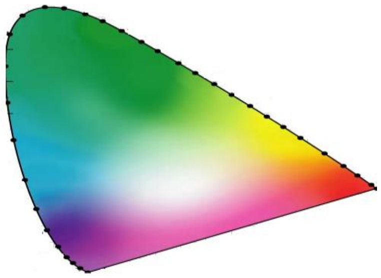

Fig. 1(a). Chromatic representation of red, blue, green and white LED signals (color online)

From this figure, it is affirmed that the intersection among three colours bestows on a signal of white LED and it also looks in white in colour. Further as far as the value of the wavelength corresponding to the different colour (signal) is concerned, red signal deals with the wavelength range of 625 nm – 750 nm blue signals manipulates with the wavelength range of 455 nm to 490 nm, where the wavelengths of green signal are chosen as 490 nm to 565 nm. When these signals are interacted among each other in such way that the intersection regime would be the wavelength ranges from 395 nm to 520 nm, which is the output signal of white LED. Early, it was understood that the generation of above said signal is due to the combination of three LEDs only. More specifically, it is realised that a signal of 395 nm–520 nm signals could be generated with the combination of three different colours of red, blue and green optoelectronic devices. Further to realise the important of white LED signal, the present paper deals with the generation of same signal with the help of photonic structures only. For example signals of red, blue and green are generated by the fiber-1, 2 and 3 respectively, where fiber 4 generated a signal of white LED with combining these three signals. As far as literature review is concerned, reference [8] deals with the similar type of works with the help of 1D photonic structure but there are three types of losses considered only. Aside this, the different application pertaining to the similar type of devices are disclosed in the reference [9],[10],[11] and [12] which deal with the sensing, communication (MUX/DMUX), computing (optical memory) and trans-receiver applications respectively. Aside these, reference [8] discloses a laser torch application using similar type of structure. In above said applications, each work has been carried out using single structure only. However the present research deals with the combination of four photonic crystal fiber to realise the white LED system. To envisage the above said work lucidly, section 2 explains the operational mechanism, whereas the supporting mathematical equation have been mentioned in the section 3. Further section 4 deals with the results and interpretation and section 5 deals with throughput efficiency of the fiber. Finally, conclusions are indicated in the section 6.

2. Operational mechanism

Basically, the operational mechanism manipulates with the structure of photonic crystal fiber which plays vital role to realise the white LED application. So, before going to discuss the operational principle, let us concentrate on the cross-sectional view of the two dimensional square type photonic crystal fiber, which is shown in the Fig. 1(b).

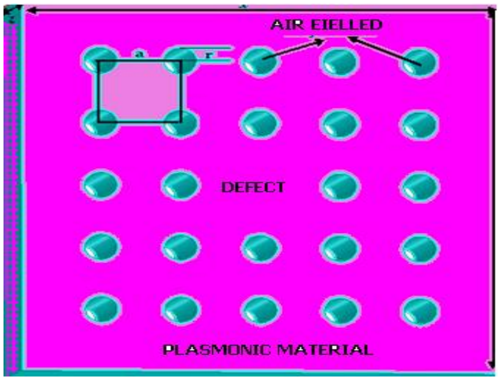

Fig. 1(b). Cross-sectional view of plasmonic based two dimensional square type photonic crystal fiber (color online)

In the Fig. 1(b), there are 24 numbers of air holes that have been etched in regular manner on the plasmonic substrate in such a way that the central part of the structure appears without air hole. This part is called as defect. The reason for choosing such structure is that it produces the generation of red, blue and green as well as white LED signals. Apart from this the configuration of the structure such as lattice spacing and diameter of air holes also play vital role for the same. Even though Fig. 1(a) seems to be the structure of photonic crystal, it is two dimensional photonic structure and it belongs to the photonic crystal fiber because in this case length is considered as 100 μm, which is more than thickness and breadth. Further moving to the operational principle, Fig. 1(c) explains about the entire work which is equivalent to the white LED.

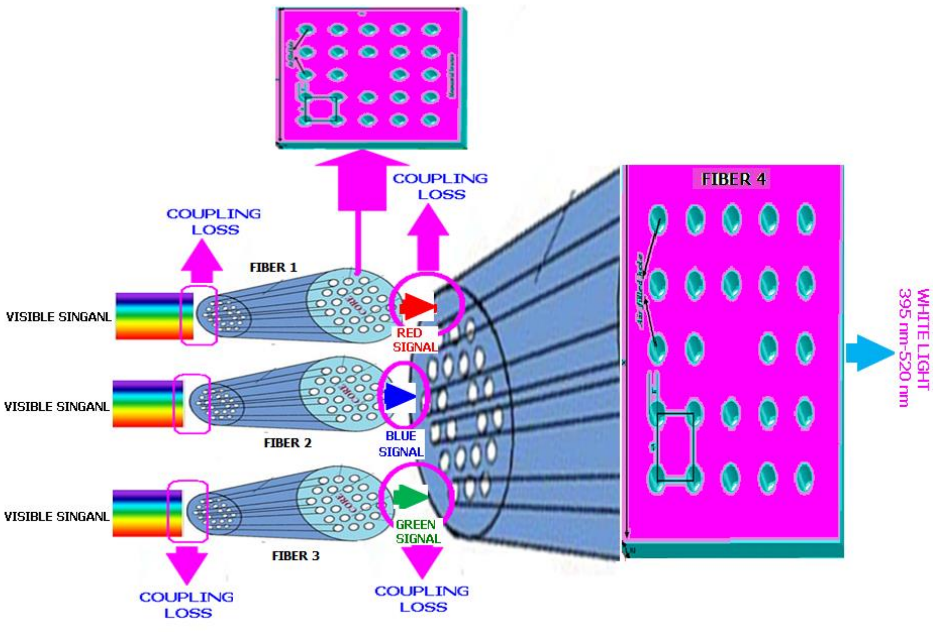

Fig. 1(c). Mechanism of the photonic fiber based white LED (color online)

Fig. 1(c) represents the working mechanism of the entire research. For example, when a signal of visible spectrum incident to the photonic crystal fiber, then the fibers have been designed in such way that fiber 1 transmits the signal of red spectrum only, whereas fiber 2 and 3 transmits the signal of blue and green spectrum respectively. However the fiber 4 combines R, B and G which will produce the signal of white LED [14]. Since the entire photonic system able to generate the signal of white LED, the system is equivalent to the white LED. As far as intrinsic mechanism is concerned the allowance of red signal, blue signal and green signal by the fibers 1, 2 and 3 depends on the refractive index of the copper based plasmonic materials at the wavelength red, blue and green spectrum. Further when these three spectrum passes through the fiber 4, the internal mechanism lies with the phenomenon of diffraction and interferences. For example; a white light spectrum would be generated at the interfering region which is confirmed from the electric field distribution and spectrum plot, Fig. 5.

3. Supporting mathematical equation

The electric field distribution inside the photonic crystal fiber is a basic principle for the generation of signal of white LED. The mathematics for supporting the same is originated from the Maxwell's electromagnetic equations. The expression for resultant of Maxwell's equations can be written as [15]

$$\nabla \times E_z(x,y) + i\omega\mu H_z(x,y) = 0 \quad 1(a)$$

$$\nabla \times H_z(x,y) - i\omega\epsilon E_z(x,y) = 0 \quad 1(b)$$

Combining these two equations and considering the free current and free charges, the resultant differential equation pertaining to the electric field can be written as [16]

$$\nabla \times \left[\frac{1}{\epsilon(x,y)} \nabla \times \mathrm{E_z}\right] = \frac{-\omega^2}{c^2} E_z \quad (2)$$

The solution of the equation (2) can be found with the help of reciprocal lattice vector as well as periodic.

$$E_z(x,y) = \int_G H_R(x,y) - G_K(x,y).e^{i(k-G).r}\,dr \quad (3)$$

The equation (3) deals the solution of an electricfield in the proposed photonic crystal fiber, where $H_R(x,y)$ is a periodic function along x and y axis and G_k (x,y) is a reciprocal lattice vector. Using equation (3) and deploying the plane wave expansion method, the electricfield emerging from the proposed fiber can be computed [17]. Further the relation between the wavelengths of the transmitted signal in terms of wavelength can be expressed as [18].

$$\lambda = \frac{2 \times \text{Planck constant} \times \text{velocity of light in vacuum}}{\text{permitivitty}_{\text{Free space}} \times \text{relative permitivitty}_{\text{Fiber}}} \times \frac{1}{(\text{Electricfield})^2} \quad (4)$$

4. Result and discussion

The objective of present research deals with the generation of the signal of white light with the help of the principle of distribution of electricfield in the fiber. The same can be obtained with the help of equation (3) through plane have expansion technique. After computing the field distribution appeared at the output end, the wavelength can be found using simple equation (4). Further to realise the same, the working mechanism is divided into two steps. In first step the generation of three signals such as red, blue and green are found with respect to the fiber 1, 2 and 3 respectively, which is shown in Fig. 1 (c), whereas in step 2, the combination of three signal, (R,B and G) take place through the fiber 4, which produce the signal of white LED. To understand the same, we have made simulation for getting the emerging signal of red, blue and green signals pertaining to the visible spectrum which act as input signal. The electric field distribution at the output end of the fibers 1, 2 and 3 and its corresponding spectrum band is shown in the Figs. 2(a) and 2(b), 3(a) and 3(b), 4(a) and 4(b) respectively.

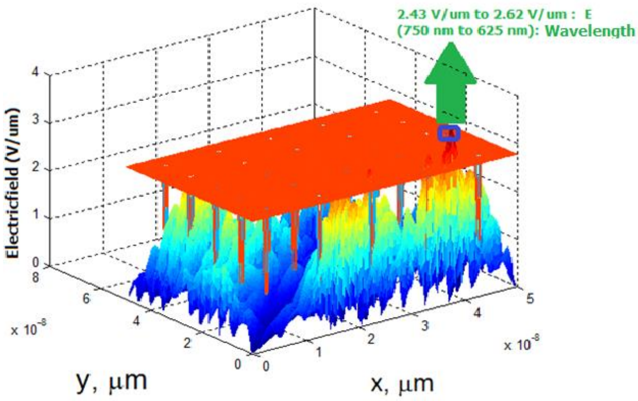

Fig. 2(a). Simulation output to generate red signals (color online)

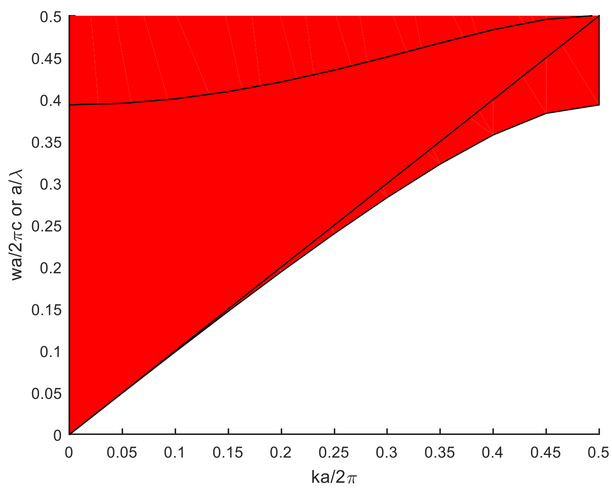

Fig. 2(b). Transmitted spectrum of red signals at fiber 1 (color online)

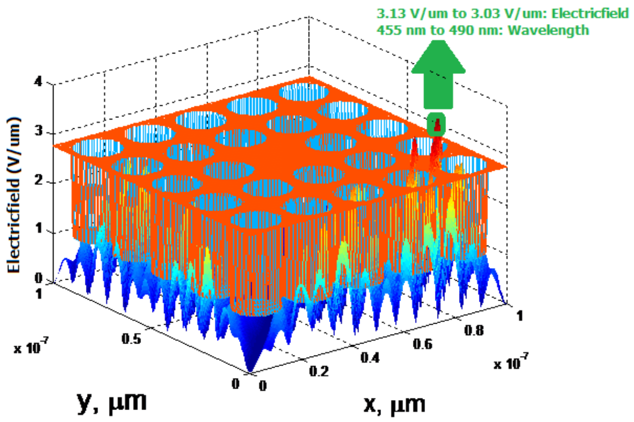

Fig. 3(a). Simulation output to generate blue signals (color online)

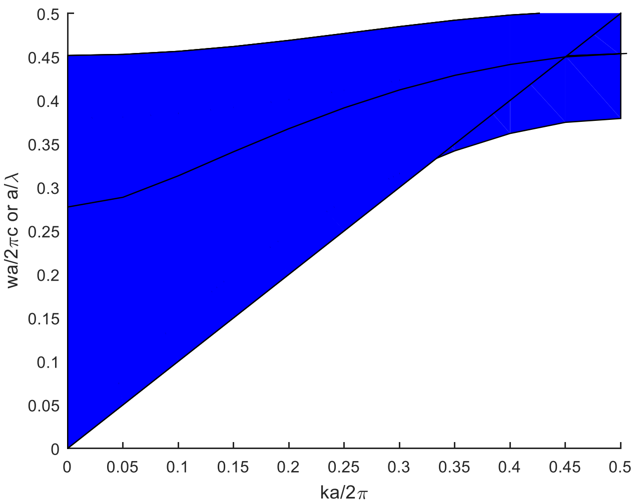

Fig. 3(b). Transmitted spectrum of blue signals at fiber 2 (color online)

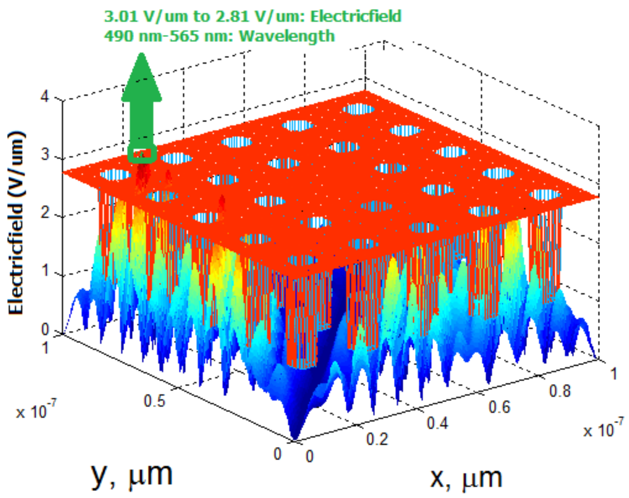

Fig. 4(a). Simulation output to generate green signals (color online)

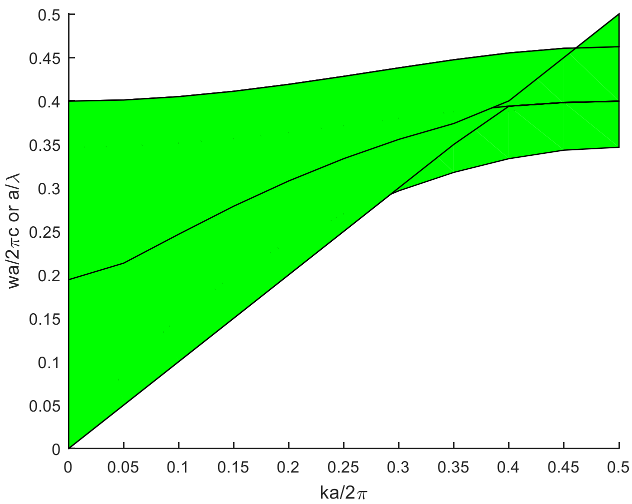

Fig. 4(b). Transmitted spectrum of green signals at fiber 3 (color online)

The Figs. 2(a), 3(a) and 4(a) are represented as the electric field distribution (V/µm) along z-axis with respect to the thickness and breadth of the fiber which is taken (µm), along x and y respectively. In the Figs. 2(a), 3(a) and 4 (a), it is found that a narrow band of field is emerging from the fiber. It indicates that when visible signal incident to the above said fiber, the said photonic crystal fiber is designed in such a way that fibers 1,2,3 allow a certain electric field and block others, which leads to the filtering applications. These fibers filter the signals from visible spectrum and allows the signal of red, blue and green spectrum. For example, the values of the electric field emerging from the fiber 1 is 2.43 V/µm to 2.62 V/µm. The computing result for wavelength corresponding to these electric field would be 750 nm to 625 nm which lies in red spectrum. Using similar type of principle, it is understood that a narrow spectrum coming from the fiber in the Figs. 3(a) and 4(a) would be 455 nm to 490 nm and 490 nm to 565 nm respectively.

Moreover the generation of the signal of red, blue and green spectrum is confirmed by the transmission spectrum which is plotted in the Figs. 2(b), 3(b) and 4(b). In these figures, normalised frequency is taken along vertical axis where the normalised wave vector is taken along horizontal axis. The spectrum in these figures represent the disersion diagram which indicates the reflected and transmitted spectrum. After analysing the Figs. 2(b), 3(b) and 4(b), it is realised that the Fig. 2(b) transmits the red spectrum only where Figs. 3(b) and 4(b) transmits the blue and green signals only. It infers that fiber 1, 2 and 3 transmits the red, blue and green signals only. After generating these three bands of red, blue and green spectrum we move to analyze the step 2 where the combination of these signal takes place at the fiber 4 and it is designed in such a way that fiber generates a signal of 395 nm to 520 nm which is represented as white LED spectrum pertaining to the Fig. 5(a) as eventually white LED generates at this ranges only. Moreover the generation of white spectrum is due to the interfering of R, B and G is shown in the Fig. 5(b).

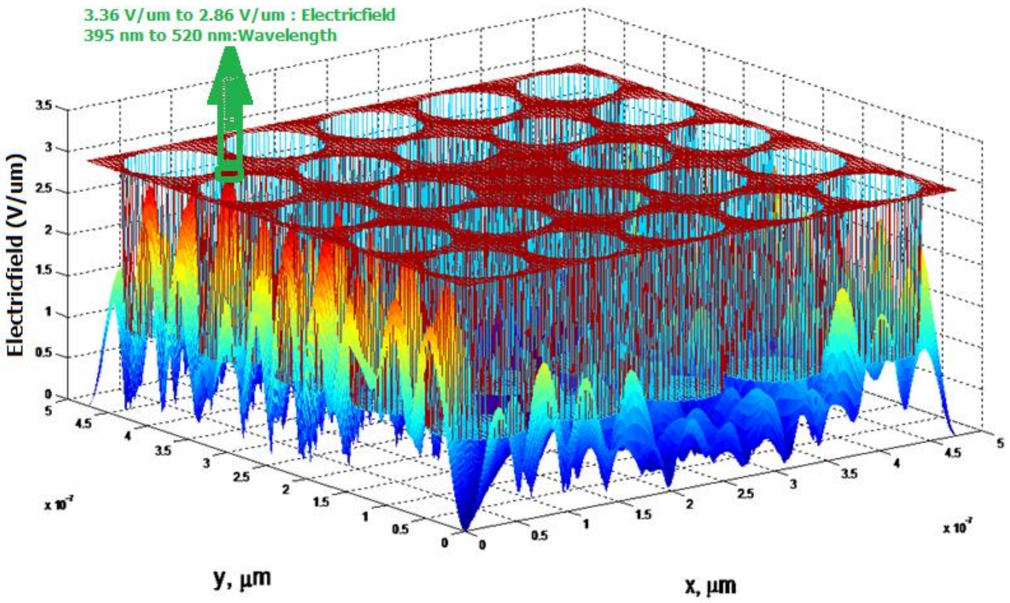

Fig. 5(a). Simulation output to generate white LED signals (color online)

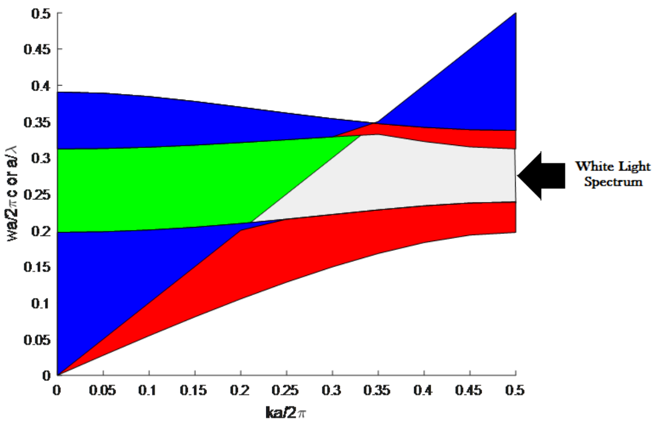

Fig. 5(b). Transmission spectrum of white light signals at fiber 4 (color online)

Fig. 5(a) represents the electric field distribution in the fiber 4 which is able to generate white light. Here the transmitted electric field in the fiber lies with the spectrum of white light. Further Fig. 5(b) also confirms the generation of white light. For example; the intersection region in the Fig. 5(b) represents the white light which is wrapped by the three spectrum of R, B and G. It affirms that due to the phenomenon of interference of R, B and G, a white light is generated. The reasons for such interesting result is due to the plasmonic material as substrate of the fiber and suitable combination of structure parameters of the proposed photonic crystal fiber. For example the lattice spacing and the diameter of the air holes is 20 nm and 8 nm, 20 nm and 6 nm, 30 nm, and 12 nm for the fibers 1, 2 and 3 respectively. Similarly, the lattice spacing and diameter of air holes of the fiber 4 is taken of 80 nm and 32 nm respectively. Further the physics of the outcome depends on the effective refractive indices of the plasmonic material pertaining to the red, blue, green signal as well as visible signal whose value is found to be less than 1. Moreover the mathematics of such interesting result lies with the interaction of plane wave expansion method with Maxwell's differential equation. Further we move to compute the coupling loss between visible source to each fiber 1, 2 and 3 and fibers 1, 2 and 3 to fiber 4. To carry out the same, the following notion has been used.

4.1. Coupling efficiency between source to fiber and fiber to fiber

The present paper deals with the visible signal as input source where the said signal impinges to the photonic crystal fiber then there will be a probability to occur a certain loss between sources to fiber. The same can be understood from the following equation as [19]

$$P_F = P_S(NA)^2 \tag{5}$$

where, P_F and P_S be the power entering to the fiber and power of the source respectively. Similarly NA is represented as the numerical aperture of the fiber. Further the above said equation is valid for the breadth of the sources which is less than the breadth of the photonic fiber (proposed structure).

The above said equation can be expressed as [20]

$$\frac{P_F}{P_S} = \left(n_{plasma}^2 - n_{air}^2\right)$$

or

$$\eta_{coup} = \left(n_{plasma}^2 - n_{air}^2\right) \tag{6}$$

Here n_{plasma} and n_{air} be the effective refractive index of substrate and air hole with respect to the visible spectrum respectively. As far as the numerical value of effective refractive index and plasmonic layer and air holes is about 0.001 and 1 respectively. After putting these values, it is realised that the coupling efficiency between source and fiber would be around 1, which enforce that no loss of the signal between source and the fiber. Again, moving to compute the coupling efficiency between fiber to fiber (fiber 1, 2, and 3 to the fiber 4), the following equation is required to find out the same [21].

$$\eta_{overall} = \eta_{geo} \times \eta_{ref} \times \eta_{ang} \quad (7)$$

Here $\eta_{overall}$, η_{geo}, η_{ref} and η_{ang} be represented as overall, geometrical, reflection and angular efficiency respectively. As far as geometrical efficiency is concerned, it relies on the size of the input fiber (fibers 1, 2 and 3) and output fiber (fiber 4). Since the size of fibers 1, 2 and 3 is less than the fiber 4, the geometrical efficiency 'is '1' (size of the fibers 1, 2, 3 and 4 are 50 nm × 50 nm, 100 nm × 100 nm, 150 nm × 150 nm and 450 nm × 450 nm respectively). Further moving to Fresnel's reflection efficiency between input to output fiber, which can be written as [22]

$$\eta_F = \left(\frac{n_{fiber1/2/3} - n_{fiber4}}{n_{fiber1/2/3} + n_{fiber4}}\right)^2 \quad (8)$$

Consider the effective refractive index of the structures 1, 2, 3 with respective to the red, blue and green signal and the effective refractive index of the fiber 4 pertaining to the white signal, the computed result for η_F would be around '1'. Further it is inferred that no reflection at the interface between input and output fiber.

Lastly the angular efficiency is brought to discuss in this forum owing to the invoking of divergence of the input signals, which can be expressed depending on the angle of the fiber as [23]

$$\eta_{ang} = 1 - (\cos\emptyset_{fiber})^{m+1} \quad (9)$$

where 'm' is called the mode of the fiber. Here the Φ_{fiber} is taken as 90^0 owing to the light emerging from the input fiber is perpendicular to the plane of the output fiber

$$So, \ \eta_{ang} = 1 \quad (10)$$

Therefore combining all these factors, the final coupling efficiency between the fiber 1 to 4, 2 to 4 and 3 to 4 is found to be 1 or coupling efficiency of 100%. To sum up, it is understood that the overall efficiency of the proposed entire photonic system is '1'.

5. Throughput efficiency of the fiber

Throughput is the actual amount of data or signals that is successfully sent/received over the communication link. It concerns about the amount of data passes through the fiber with respect to the loss and the capacity of the fiber. The throughput is presented in form of byte per second [kbps, Mbps, Gbps, Tbps or more]. It can be expressed [24]

$$\text{Throughput} = \text{Efficiency} \times \text{bandwidth} \quad (11)$$

where efficiency depends on the transmission delay and propagation delay time.

The same efficiency can be expressed as [24]

$$Efficiency = \frac{T_t}{T_t + T_p} \quad (12)$$

Transmission delay (T_t) is the time needed to push all the packet bits on the transmission link. It mainly depends upon the size of the data and channel bandwidth (in bps). Where the propagation delay is the time taken for one bit to travel from one end of the link to the other. The bits travel in the form of electromagnetic signals. The speed at which electromagnetic signals propagate is determined by the medium through which they pass. Apart from this, due to the delay process, the transmitted data bandwidth is less than channel capacity in the fibers 1, 2, 3, and 4. Using the equations (11) and (12), the channel capacity of the proposed fibers and throughput of each fiber is indicated through graphical representation which is shown in the Fig. 6.

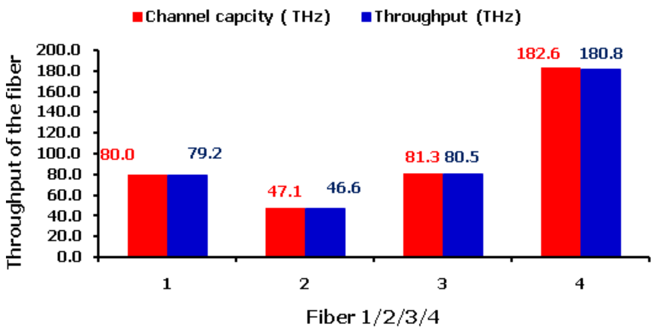

Fig. 6. Representation of channel capacity and throuhput of each fiber (color online)

Fig. 6 represents the capacity of each fiber and the efficiency of each fiber pertaining to its transmitted bandwidth. From the figure it is found that 79.2 THz, 46.6 THz, 80.5 THz and 180.8 THz bandwidth of signal is transmitted with respect to the channel capacity of 80.0 THz, 47.1 THz, 81.3 THz and 182.6 THz in the fibers 1, 2, 3 and 4, respectively. In this case, the efficeincy of the fiber is about more than 99 %.

6. Conclusions

The generation of white LED signal is realised with the help of photonic system via plasmonic based photonic crystal fiber. The principle of mechanism deals with the transportation of the electric field which is carried out with the help of plane wave expansion technique. The operational mechanism relies on the nature of material as well as structure parameters including the lattice spacing and the diameter of air holes. Similarly the physics of such interesting outcomes deals with the effective refractive indices where the mathematics manipulates the solution of maxwell's differnetial equation. The outcomes of simulation results is made through the analysis of electric field distribution which is verified by the transmission spectrum. Moreover it is also realised that the efficiency of the fiber is more than 99% and the transmitted bandwidth is in the order of THz. Finally, the outcome of the simulation results infers that the photonic crystal fiber based system could be a right candidate to realise the equivalent of white LED.

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