Indian Journal of Pure & Applied Physics
Vol. 62, July 2024, pp. 547-552
DOI: 10.56042/ijpap.v62i7.9028

# Undistorted Delivery of Ultra-short Laser Pulses through Triangular Core Fiber

Manju, Sonia, Babita* & Meenakshi
Department of Physics, Baba Masthnath University Rohtak, Rohtak Haryana 124 001 India

*Received 23 February 2024; accepted 1 May 2024*

This paper presents triangular core fiber for single-mode operation. The fiber supports single mode at a wavelength of 1550-nm, and it has an extremely large mode area of 2000 $\mu m^2$. With peak power of 85.4-kW at 1550 nm wavelength, fiber design demonstrates undistorted delivery of 100 fs laser pulses. We have used Transfer matrix method to analyse the fiber. The split-step Fourier method has been used to solve the non-linear Schrodinger equation. Raman's response and self-steepening have also been taken in to account. In this paper, we report the numerical demonstration of propagation of 100-fs pulse with peak power of 85.4-kW at 1550-nm wavelength through 2.5 m long fiber. The ratio of dispersion length to nonlinear length has been kept as 1 for the delivery of undistorted pulses.

**Keywords**: Single mode fiber; Ultra-short pulses; Pulse propagation; Large mode area; Triangular core fiber

## 1 Introduction

Researchers are very interested in single-mode fibers because of its use in many fields like high power lasers, amplifiers, and optical communication. In order to prevent mode conflict and intermodal dispersion, single-mode fibers are most commonly utilized than multimode fibers. These fibers have a long range of pulse preservation. Although the likelihood of mode coupling is reduced in single mode fibers, the confinement of the pulses in the narrow core region causes nonlinearities in the fiber. To propagate high energy ultra-short laser pulses, mode area should be high to reduce nonlinear effects in the fiber. By expanding the core diameter, we can reduce the nonlinear effects. When we increase the core diameter, coupling problems appear and the number of modes grows. Therefore, we require single-mode fiber with a large mode area in order to overcome these challenges[1,2].

A lot of research has been done in recent years to meet the requirements of single mode operation and large mode area. Examples of these types of fibers are Rod type fibers, Multi-Core optical fibers, Dual-core resonant leaky fibers, Segmented Cladding Fiber (SCF), Photonics Crystal Fibers (PCF), Photonic Band Gap Fibers, and Leakage Channel Fibers (LCF). But the process of fabricating these fibers is complex and specific to the uses.

SCF exhibits a non-uniform refractive index with angularly changing zones of high and low index. SCF may operate in a single mode throughout a broad wavelength range while preserving a large mode area, However bend loss and mode coupling remains an issue with the design[3,4]. PCF is the layout of a sizable mode area with air holes spaced evenly throughout the fiber's length. Because of the huge core size in PCF, mode spacing is insufficient, which leads to mode coupling[5]. Photonic band gap hollow-core (PBG-HC) fibers exhibit low loss, extreme bending robustness, and single-mode operation; however, scaling PBG-HC fibers to large core diameters is a major challenge[6]. Fiber designed by Ramachandran *et al*., can deliver ultra-short laser pulses with high peak power, with a mode area of about 3200 $\mu m^2$. The fiber length for delivery of USPs is 12 m. To excite the higher- order modes, long-period fiber gratings have been used. Pulse propagation through the fiber has shown enough spacing between the modes due to which possibility of mode coupling has reduced. They have reported that the loss due to propagation in HOM, and input splice is less than 0.2 dB, however the use of gratings has increased the complexity of the fiber. Higher mode fibers show a larger mode area and less sensitivity to mode coupling, but the limitation is in complex design due to the use of gratings[7,8]. Babita *et al*., proposed a design of three-layered step-index fiber of mode area 1900-$\mu m^2$. Fiber has shown the delivery of pulses of 100-fs, peak power 55-kW at wavelength 1550-nm up to the length of 4 m. Fiber has maintained enough spacing between $LP_{01}$ and $LP_{11}$ modes[1]. Shaoshuo *et al*., proposed a

*Corresponding author: (E-mail: babitaphy@gmail.com)

Single RingSCF (SR-SCF) fiber in which a thin ring has been inserted between non-uniform cladding and high indexed core of SCF. Compared to SCF, mode spacing between $LP_{01}$ and $LP_{11}$ has been improved hence mode coupling has been reduced. They reported single mode operation from wavelength 1 μm to 1.7 μm with mode area up to 1000 $\mu m^2$[4]. Andreana *et al*., designed an ultra-large-core Kagome HC-PCF for the undistorted delivery of nanojoule femtosecond pulses. A Cladding structure was introduced in which Kagome lattice includes webs of silica surrounded by air. This structure provides low overlapping with silica. Ultra short pulses of 15 fs launched through a 44 μm mode field diameter, fiber shows dispersion of 1ps/nm/km and attenuation of 80 dB/km. When the suggested Fiber is bent with a radius of less than 50 mm, its bending loss is 3 dB[9]. Liang *et al*., proposed an air filled anti-resonant hollow core fiber of length 5m rewound on an aluminium plate of radius 20 cm. The proposed fiber design has shown the damage-free delivery of pulses of wavelength 1064 nm of maximum peak power 3.5 MW through the fiber. They have reported the beam quality factor ($M^2$) is less than <1.6. Fiber shows the attenuation of 0.18 dB/m for 1064 nm wavelength along the fiber[13]. In order to achieve single-mode operation with a large mode area, we have designed a triangular core fiber in this paper. Triangular profiles can confine modes to smaller beam diameters and have reduced loss as compared to step-index fibers[10]. The proposed fiber has a large mode area of 2000 $\mu m^2$ while maintaining single-mode operation. The suggested fiber's v-parameter is less than 4.38, indicating that it is single mode, which resolves the mode coupling problem.

## 2 Method of Analysis

Transfer matrix method (TMM) has been used to analyse the fiber. To study pulse propagation we have used split–step Fourier method. In split-step Fourier method we have solved second order Non-linear Schrodinger equation.

### 2.1 Transfer Matrix Method

TMM considers a graded index fiber as a multilayer structure of refractive indices $n_1$, $n_2$, ….$n_n$. Fiber has permeability $\mu$ and permittivity $\varepsilon$ depending on the length $r$. The incoming and outgoing waves are characterised by matrix relations. When we apply boundary conditions at the ends of the profile, we get characteristics equation from which we can get the mode indices.

$$r^2\frac{d^2R}{dr^2}+r\frac{dR}{dr}+\left[\left(k_0^2n_p^2-\beta^2\right)r^2-l^2\right]R(r)=0 \quad \text{... (1)}$$

The modal field is defined as

$$\Psi(\mathrm{r},\varphi,\mathrm{z},\mathrm{t})=\mathrm{R(r)}\begin{bmatrix}cosl\phi\\ sinl\phi\end{bmatrix}expi(\omega t-\beta z) \quad \text{... (2)}$$

Where $l$ represents Azimuthal quantum number ($l$ = 0, 1, 2, 3 . . . . . .), $\beta$ is propagation constant of mode. The process is same for $l$=0 and $l$≠0. For $l$=0 the equation can be written as

$$r^2\frac{d^2R}{dr^2}+r\frac{dR}{dr}+\left[\left(k_0^2n_p^2-\beta^2\right)r^2\right]R(r)=0 \quad \text{... (3)}$$

The general solution of the above equation when $\beta^2<k_0^2n_p^2$ is

$$\mathrm{R(r)}=A_pJ_0\left(k_pr\right)+B_pY_0\left(k_pr\right) \quad \text{... (4)}$$

The general solution of the equation for $\beta^2>k_0^2n_q^2$ is given by

$$\mathrm{R(r)}=A_qk_0\left(k_qr\right)+B_qI_0\left(k_qr\right) \quad \text{... (5)}$$

Where $k_p^2=k_0^2n_p^2-\beta^2$, $k_q^2=\beta^2-k_0^2n_q^2$

In the Scalar Approximation, according to boundary conditions R(r) and $\frac{dR}{dr}$ are continuous at each interface. The relation between the coefficient of two consecutive layers is given in matrix form such as the coefficient ($A_{p+1}$, $B_{p+1}$) and its preceding layer coefficient ($A_p$, $B_p$) is given by

$$\begin{bmatrix}A_{p+1}\\ B_{p+1}\end{bmatrix}=\begin{bmatrix}e_p & f_p\\ g_p & h_p\end{bmatrix}\begin{bmatrix}A_p\\ B_p\end{bmatrix}$$

We can calculate the parameters $e_p, f_p, g_p, h_p$ from analysis of initial value of β. We can relate the coefficients ($A_N$, $B_N$) and ($A_1$,$B_1$) by using above 2×2 matrix, where N and 1 represents the inner layer and the outer layer respectively, so the matrix is written as

$$\begin{bmatrix}A_N\\ B_N\end{bmatrix}=\begin{bmatrix}S_{11} & S_{12}\\ S_{21} & S_{22}\end{bmatrix}\begin{bmatrix}A_1\\ B_1\end{bmatrix}$$

Where $S_{11}$, $S_{12}$, $S_{21}$, $S_{22}$ are the elements of the transfer matrix method. This matrix is product of the various matrices which are of the order of (2× 2).

Guided mode:-

We have taken the condition of β $>k_0n_1$ for the guided mode. The field is finite at $r=0$ and $r=\infty$. The coefficient $B_N$ and $B_1$ must also satisfy.

$B_1=0$, $B_N=0$, $S_{21}=0$,

This is an eigen value equation. Here in this case by scanning $S_{21}$ ($\beta$) in the $\beta$-axis we can obtain a propagation constant for the guided mode.

### 2.2 Split-step Fourier Method for Pulse Propagation In Fiber

Non-linear Schrodinger equation (NLSE) has been used to study the propagation of pulses through the fiber given by

$$\frac{\partial A(t,z)}{\partial z}+\frac{\alpha}{2}A+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial T^2}-\frac{\beta}{6}\frac{\partial^3 A}{\partial T^3}=i\Gamma\{(|A|^2A)+\frac{\iota}{w_0}\frac{\partial(|A|^2A)}{\partial T}-T_R A\frac{\partial|A|^2}{\partial T}\} \quad ...(6)$$

Where, $\Gamma$ is Fiber's non-linearity, $\alpha$ is fiber loss, $\beta_3$ denotes the fiber's third-order dispersion, and $\beta_2$ denotes the fiber's second-order dispersion. The central frequency is denoted by $\omega_0$, the Raman constant by $T_R$ and the pulse envelope amplitude at spatial position z in time t is represented by A(t, z). The value of $\beta_2$ and $\beta_3$ can be calculated by using the following relation[11].

$$\beta_2=-D\frac{\lambda^2}{2\pi C}\ \beta_3=\frac{\partial D}{\partial\lambda} \quad ...(7)$$

Nonlinearity parameter is defined as

$$\Gamma(\omega_0)=\frac{n(\omega_0)\omega_0}{cA_{eff}} \quad ...(8)$$

Where, $n$ is the non-linear refractive index of the fiber material.

The Split-step Fourier method yielded the solution to the Non-linear Shrodinger Eq. 6. The pulses are distorted along the fiber's length by dispersion and nonlinearity. The fiber's length is first divided into segments. The pulses propagate from segment to segment. Dispersion and nonlinearity act independently in the fiber. We consider the pulse propagation for the small length *h*. Dispersion dominates in the first step and nonlinearity is zero. The next step has zero dispersion and nonlinearity acts. Accuracy can be achieved when pulses propagate from *z* to *z*+*h*. At the end of the fiber, both effects dispersion and nonlinearity compensate each other. The dispersion length $L_D$ and nonlinear length $L_{NL}$ indicated in the following equations reflect the effects of these parameters[11].

$$L_D=-\frac{2\pi c\tau^2}{\lambda_0^2 D}\ L_{NL}=\frac{\lambda_0 A_{eff}}{2\pi np} \quad ...(9)$$

where $n$ is the nonlinear refractive index of the fiber material, $P$ is the peak power, $\tau$ represents the pulse duration, $\lambda_0$ represents the center wavelength, and $c$ is the speed of light in a vacuum. $D$ represents the dispersion and is given by

$$D=-\frac{\lambda_0}{C}\frac{d^2 n_{eff}}{d\lambda_0^2} \quad ...(10)$$

P represents peak power and is given by

$$p=\frac{\lambda_0^3 D A_{eff}}{4\pi^2 c n\tau^2} \quad ...(11)$$

The fiber's effective area of mode ($A_{eff}$), is a measure of the power density inside the fiber.

The effective area has a strong influence on nonlinear effects in the fiber[11].

## 3 Fiber Design

The propagation of pulses through the fiber is highly affected by nonlinearity and dispersion. To minimise these effects, mode area should be large. When we increase the mode area, coupling issues increase. To compensate for the issues mentioned above, we propose a triangular core fiber with refractive index profile given by.

$$n(r)=\begin{cases} n_1\left(1-2\Delta\left(\frac{r}{a}\right)^q\right)^{1/2} & for\ 0\le r\le a \\ n_1(1-2\Delta)^{1/2}\approx n_1(1-\Delta)=n_2\ for\ r\ge a \end{cases} \quad ...(12)$$

Where, $a$ denotes the fiber's core, $n_1$ and $n_2$ the refractive indices of the core and cladding, respectively, and $q=1$ represents the triangular properties of the refractive index profile of the fiber. The fiber's outermost jacket is doped with Ge in pure silica and depressed cladding is achieved by F doped silica. The refractive index of outer most cladding is 1.4404 and that of inner cladding is 1.4401.The width of depressed cladding is represented by $b$ and that of outer cladding is represented by $c$. The variation of refractive index along with radial position in the fiber design is shown in the Fig 1. The values of the fiber parameters are given below:-

$a$ = 35 µm, $b$ = 2.2185 µm, $c$ = 25.2815 µm, $\lambda$ = 1550 nm, $n_1$ = 1.4406

The parameters are carefully chosen where we have obtained single mode operation with large mode area of 2000 µm$^2$ and the ratio of dispersion length and nonlinear length is equal to 1.

Fiber shows single-mode operation at a large value of core radius. We have used Gaussian approximation method to calculate the $A_{eff}$ of the fundamental mode[1].

The effective mode area of the fundamental mode is 2000 μm$^2$. The v-parameter has been calculated by the Eq.[12].

$$V = ak\sqrt{n^2(0) - n^2(a)}$$

Where k=2π/λ ... (13)

The maximum value of v-parameter for the designed fiber is 4.17, hence it shows that the fiber supports single mode only.

## 4 Results and Discussion

The main factors influencing pulse propagation within fibers are dispersion and non-linearity. Pulse propagation can be characterized by $L_D/L_{NL}$ where $L_D$ and $L_{NL}$ can be calculated from Eq. 9. If $L_D/L_{NL}<1$ dispersion dominates over non-linearity along the fiber therefore pulses get broadened in the absence of any chirp otherwise compression and stretch can be seen according to the initial chirp. If $L_D/L_{NL}>1$ non-linearity dominates over dispersion therefore pulses do not maintain their original shape. At $L_D/L_{NL}\approx1$ dispersion and nonlinearity balance each other and fundamental soliton propagation is obtained[11]. We have studied the propagation of pulses by solving non-linear Schrodinger Eq. 6 by split-step Fourier methods. In the reported fiber, the value of dispersion at wavelength 1550nm is –32.58 ps/(nm/km). Fiber shows pulse propagation of 100 fs of Peak power 85.4 kW. We have taken the value of $n$=2.4× $10^{20}$ $m^2/w$ [1]. Raman scattering and Self-steepening are also considered. Self- steepening is defined as $s = 1 / \omega_0\tau$ where, $\omega_0$ is the central frequency of the pulse and $\tau$ is its width. The definition of the Raman scattering method is $\tau_R = T_R/\tau$ where $T_R$ represents the Raman time constant[1]. The value of $T_R$=3 fs at a wavelength of 1550 nm has been utilized. We have kept the value of $L_D/L_{NL}$=1 to compensate the nonlinearity and dispersion. Third-order and second-order dispersion calculations have been made. The calculated value of third-order dispersion is in the power of $10^{-5}$, which balances the fiber's nonlinear effect.

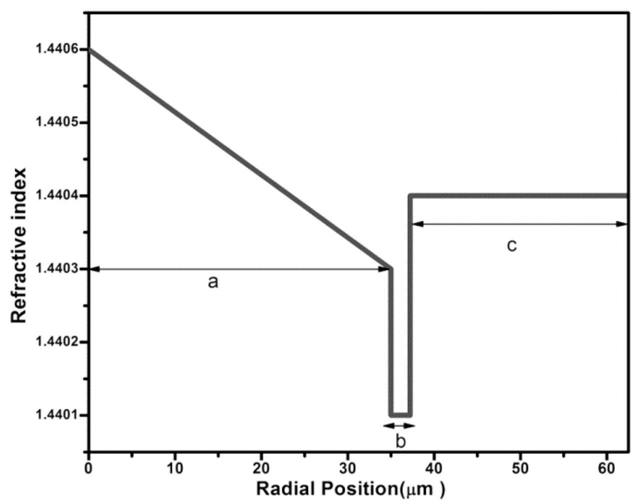


Fig. 1 — Variation of refractive index along with radial position in fiber design

We have investigated the propagation of sech and Gaussian pulses through the fiber. Fiber shows distortion-less delivery of 100 fs Gaussian pulses and sech pulses of peak power 85.4 kW up to the length of 2.3 m and 1.4 m respectively. Input output profile of Gaussian pulse through 2.3 m length of the fiber is shown in Fig. 2. Evolution of pulse and corresponding contour profile are shown in Fig. 3(a & b) respectively.

Apart from Gaussian pulses we have also studied propagation of sech pulses. Input output profile for sech pulses is shown in Fig. 4. Evolution of sech

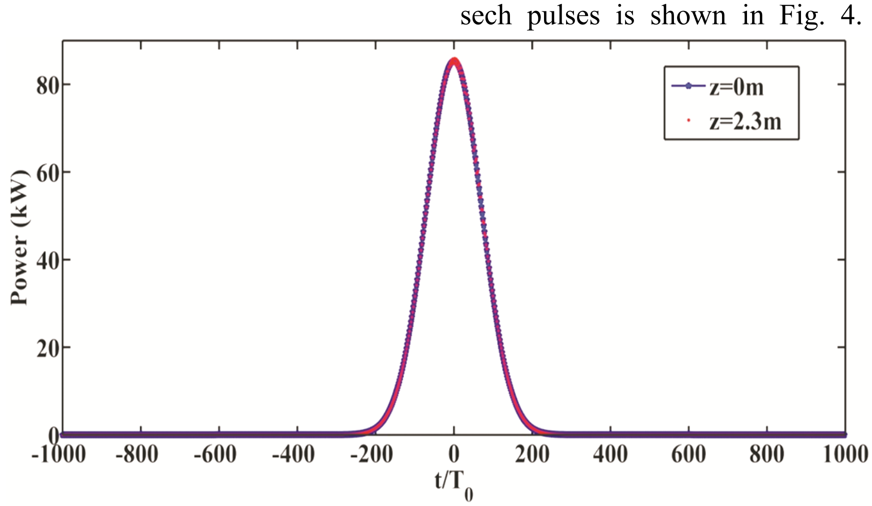


Fig. 2 — Input output profile for Gaussian pulses

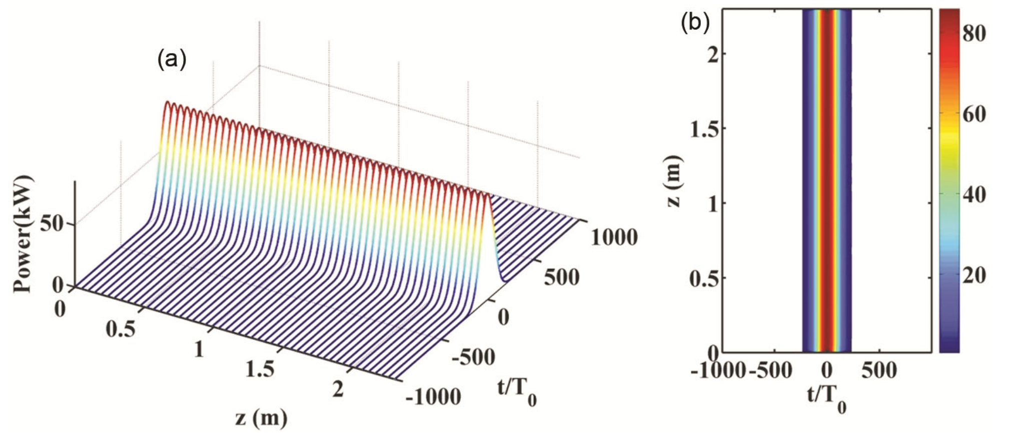


Fig. 3 — (a) Gaussian pulse propagation within a 2.3-meter-long fiber (b) corresponding contour profile of the pulse

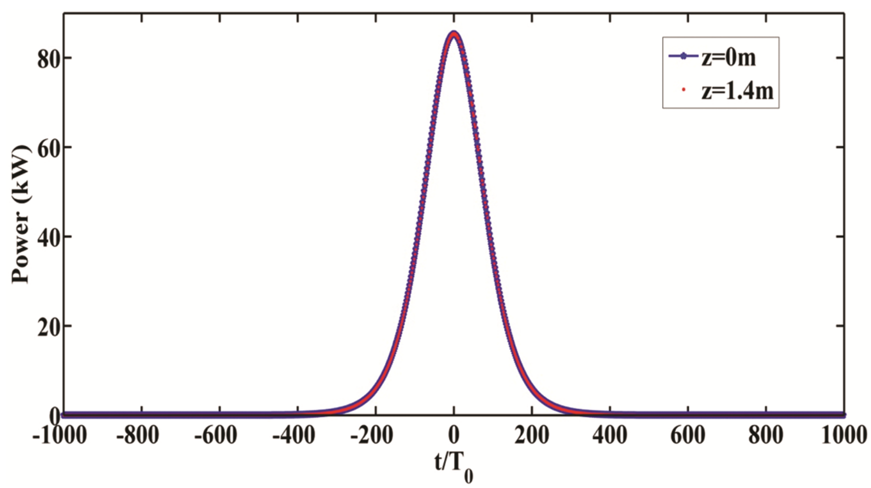


Fig. 4 — Input output profile of sech pulses

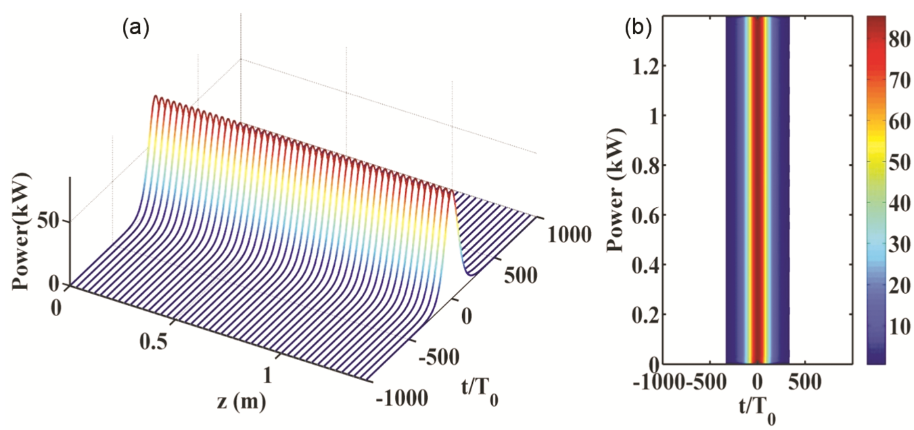


Fig. 5 — (a) sech pulse propagation with in a 1.4 m long fiber (b) corresponding contour profile

pulses along with contour profile is given in Fig. 5(a & b) through 1.4m length of the fiber. From the figure we can conclude that distortion-less delivery of sech pulses have been obtained through 1.4 m length of the fiber.

## 5 Conclusion

We have designed a triangular core fiber with extremely large mode area of 2000 $\mu m^2$ to study the delivery of high power ultra-short laser pulses of wavelength 1550 nm. Fiber supports single mode operation. We reported the delivery of 100 fs pulse with peak power of 85.4 kw at wavelength 1550 nm. We numerically demonstrated the distortion-less delivery of Gaussian pulses and sech pulses of peak power 85.4 kW through 2.3 m and 1.4 m length of the fiber respectively. The proposed fiber design should be beneficial in fields like optical communication, biomedical applications and multiphoton microscopy.

**Acknowledgement**

The authors would like to thank [Baba Masthnath University, Rohtak, India] for their valuable guidance and assistance during this research. Additionally, we acknowledge the participants of the study for their willingness to contribute to the data.

## References

1 Hooda B, Rastogi V & Kumar A, *Opt Commun*, 293 (2013) 108.
2 Hooda B & Rastogi V, *Prog Electromagn Res B*, 51 (2013) 157.
3 Hooda B & Rastogi V, *Opt Quant Electron,* 46 (2014) 397.
4 Shaoshuo M, Tigang N, Jing L, Li P, Chuanbiao Z & Xiaodong W, *Appl Opt*, 55 (2016) 9954.
5 Peng X, Mielke M, Booth T, *Opt Exp*, 19 (2011) 923.
6 Michieletto M, Jens K Lyngsø, Christian Jakobsen, Jesper Lægsgaard, Ole B & Thomas T, *Opt Exp*, 24 (2016) 7103.
7 Ramachandran S, Nicholson J, Ghalmi S, Yan M, Wisk P, Monberg E & Dimarcello F, *Opt Lett,* 31 (2006) 1797.
8 Nicholson J W, Ramachandran S, Ghalmi S, Yan M F, Wisk P, Monberg E & Dimarcello F V, *Opt Lett*, 31 (2006) 3191.
9 Andreana, Tuan L, Wolfgang D & Angelika U, *Opt Lett*, 44 (2019) 1588.
10 Saifi M A, Jang S J, Cohen L G & Stone J, *Opt Lett*, 7 (1982) 43.
11 Agrawal G P, Nonlinear Fiber Optics, Chaps, Academic,San Diego, (2001) 2.
12 White K I, *Electron Lett*, 18 (1982) 725.
13 Liang G L, Zhu J, Wang X, Wu Y, Yu D & Han F, *Photonics, 10* (2023) 416.