Final Progress of Research

[from 01-04-2016 to 31-03-2018]

Project Title: Modeling And Analysis Of Single Mode Fiber Raman Gain Amplifiers With Tellurite Base And Subwavelength Diameter Optical Fibers And Comparison With Conventional Fiber Characteristics.

Award Letter: F6-6/2016-2017/EMERITUS-2015-17-GEN-8507/(SA-II), dated April 1, 2016.

As an Emeritus Fellow, I express my deep gratitude to University Grants Commission (UGC) for providing me the opportunity to consolidate research in Fiber Optics and Photonics at the Department of Electronic Science, Calcutta University.

Now, so far as the topic declared in the project as subwavelength diameter optical fibers (SDOF) and comparison with conventional fiber characteristics is concerned, we are extremely successful to publish papers in reputed international journals **[1, 2, 3]**. In case of tellurite based FRGA and comparison to conventional fiber characteristics, we have published one paper **[4]** and now have understood deeply the principles of tellurite based FRGA. However, during the tenure, we have explored one new emerging field in liquid infiltrated air holes in the photonic crystal fiber (PCF) to achieve ultraflat zero dispersion which will be suitable to produce supercontinuum generation (SCG). In this field, we have published two papers in Applied Optics **[5, 6]** and one in Elsevier journal **[12]** . Also, we have tested our user friendly program based on finite difference method (FDM) which has been used to publish not only to interpret PCF **[5, 6]** but also planar waveguides in integrated optics for crucial structure **[13]**. In parallel, we have published six papers in the context of conventional fiber characteristics with nonlinear **[7, 8]** and linear media **[9, 10, 11 and 14]** . Over two years, we have been able to publish fourteen papers in international journals of repute **[1-14],** get accepted one **[15]** and communicated two in such journals **[16, 17]** . The seventeen papers that are published, accepted and communicated during the tenure are presented in References in Section A. **We have duly acknowledged UGC for financial support in all these papers**.

Based on the above research activities, five Ph.D theses were submitted, two students were awarded the Ph.D degree and one is expected to be submitted shortly. We are grateful to UGC for providing the infrastructural facilities through contingency support of emeritus fellowship project. The list of the theses with their titles is presented in Section C.

(A) Journal publications done during Fellowship tenure from 01-04-2016 to 31-03-2018

(I) Subwavelength diameter optical fibers (SDOF) and comparison with conventional fiber characteristics

Firstly, we report a simple and straightforward approximate analysis to investigate the effect of Kerr type nonlinear optical processes (NOP) in step index SDOF based on Marcuse method in single mode region. Optimum core diameters of such fibers, predicted by us, together with relevant core nonlinearity coefficient and effective area are seen to be compatible with the analytical values indicating the validity of this novel application of the elegant approximate method. However, the corresponding values, obtained by earlier variational method, show larger discrepancy with analytical findings in comparison with ours. Also, maximum enhancement of NOPs within single mode region, confirming almost the analytical method, assures less diffraction. Formulations, coupled with simplicity and novelty of the present analysis, should find wide use by system users and experimentalists in this emerging area **[1]** .

Secondly, a significant effect of nature of refractive index grading in the core of SDOF on their performance characteristics in single-mode region is predicted and reported, for the first time, in connection with achievement of waveguide enhancement of Kerr NOPs. The analysis is based on a straightforward approach involving Marcuse spot size formulations for single-mode graded index fibre (SMF). Our formulations and results provide useful information and insight for optimum transverse dimensions of graded index fibre together with normalized core nonlinearity coefficient corresponding to profile exponent of the power law profile and should invite attention of system designers **[2]** .

Thirdly, we investigate the Kerr NOPs in the case of a trapezoidal index SMF based on recently formulated and appropriate Marcuse-type relations for spot size in terms of normalized frequency corresponding to such fiber having various aspect ratios. With the help of these relations, we have analyzed the maximum NOP in these fibers having prospective merits of tight light confinement in the subwavelength diameter waveguiding region. The comparative investigation reveals that the aspect ratio having a value of 0.7 is the most promising candidate for maximum optical nonlinearity, constructional convenience, and less diffraction. The analysis should be attractive for system users as a ready reference **[3]** .

(II) Single mode Fiber Raman Gain Amplifiers with Tellurite base and comparison with conventional fiber characteristics

Here, an investigation on the effect of practically possible upper and lower parabolic dips in the refractive index profile of the inner core of the coaxial fiber Raman gain amplifier is reported using matrix method for single pump. It is seen that for lower parabolic dip, the tolerable limits of dip parameters correspond to dip depth of 0.25% and dip width of 25% of the respective parameters for ideal step index profile case and agree with the earlier predicted linear dip. However, for upper parabolic dip, one gets higher gain and better flatness at these limits. Even up to 1% of the dip depth for 25% of dip width or 75% of dip width for 0.25% of the dip depth or 0.5% of dip depth and 50% of dip width, one can expect performance as good as that of the ideal one. However, since system designers will be aimed to produce ideal profile, our recommendation is to keep tolerable limits within 0.25% of dip depth and 25% of dip width of respective parameters. But, one can accept profile with upper parabolic dip if there is deviation within the above relaxation limits for such dip **[4]** .

(III) Liquid infiltrated PCF characteristics suitable for SCG

In this emerging area, based on a simple but accurate semivectorial solution of Helmholtz's equation by the finite difference method (FDM) devised with a mode–field convergence technique, we have shown an interesting and significant effect showing an almost ultraflat zero group velocity dispersion (GVD) in PCF when the holes of the first ring of the fiber are filled with water. Crosschecking our results with earlier results involving a deeply involved multipole method for the central core of PCF filled with water and fused silica, our observation in the case of filling the first ring holes with water reveals potential information in studies of SCG **[5]** .

Then, using a glycerine-water solution with various concentrations, we investigate the dispersion characteristics of PCF by selective filling of holes. Our analysis is based on a simple but accurate semi-vectorial solution of Helmholtz's equation by the FDM devised with a mode–field convergence technique and crosschecked by results with those from a deeply involved multipole method. Significantly, a better ultra-flatness but near-zero GVD is revealed with a 20% glycerine-water solution that is superior to pure water of a very recent case when the holes of the first ring of the fiber are filled. This versatile effect in management of holes of identical diameter with liquid is expected to play a guiding role in studies of SCG **[6]** .

PCFs capable to operate endlessly in single moded regime offer varied and novel applications of practical interests. Hence, appropriate coupling with an optical source, working at wavelengths of well known significance is required for the effective functioning of these fibers. We present here an optical coupling scheme of such a single mode PCF with a laser diode through easily fabricable hemispherical microlens using ABCD matrix formulation. We, also, report the best distance of separation of the laser diode from PCF producing the maximum coupling. Our result

should find wide use by system designers and engineers to, appropriately, calibrate PCFs based on our formulation devoid of complexity of the deeply involved numerical method.

With PCF, in linear integrated optics, we develop FDM and analyse some practically interesting planar waveguide structures and develop the proper FDM algorithm to predict the relevant transverse electric and transverse magnetic modes with their propagation constants (b) over a long range of normalised frequency (V). In order to crosscheck our results from FDM, we use the step index profile, parabolic index profile and complementary error index profile as a test case to standardise our program. Then, with our program, we consider two more structures such as, diffused planar waveguide and planar directional coupler, to predict the corresponding b−V curves which were yet to be, completely, analysed by FDM **[13]**.

(IV) Other works relevant to advance research in conventional fiber characteristics with

(a) With Nonlinear Media

In this area, we propose a simple method to compute the first higher order mode cutoff frequency of a SMF in the presence of optical nonlinearity. We consider optical Kerr-type nonlinearity for these fibers having dispersion-shifted and dispersion-flattened profiles. Our analysis involves the Chebyshev method but introduces a linearization of cubic terms of fields due to Kerr-type nonlinearity. Our results are shown to match, excellently, with the available exact numerical values. Thus, this formulation and stepwise algorithm should be considered as a simple but accurate alternative to deeply involved numerical technique and used as a guideline in calculating and minimizing the modal noise in nonlinear SMFs **[7]** .

Then, we investigate the nonlinear propagation characteristics of trapezoidal index SMF involving the exact numerical linear and nonlinear spot sizes and their relative change with respect to aspect ratio. From comparison of normalized spot sizes in absence and presence of Kerr nonlinearity, it is seen that nonlinear effect is more pronounced in lower values of normalized frequency for each aspect ratio. Further, for near cut-off propagation, the triangular index fiber excels in performance in respect of percentage change of spot sizes and fractional core power **[8]** . Based on **[8]**, we investigate the effect of Kerr nonlinearity on the angle of beam divergence of single-mode trapezoidal index fibers from its linear and nonlinear values. From comparison of angle of beam divergence in presence and absence of Kerr nonlinearity, the nonlinear effect for each aspect ratio is observed to be more pronounced in lower values of normalized frequency. Moreover, the triangular index profile supersedes the other index profiles in respect of relative change of angle of beam divergence. It should give the system users and developers a much better control over far-field related calculations and can be widely used for experiments in presence of optical nonlinearity **[17]**.

(b) With Linear Media

Here, a detailed variational analysis of trapezoidal index SMF to investigate its propagation characteristics involving two simple approximations of fundamental mode is presented. It is shown in respect of computation of normalized field that the single parameter variational function having Gaussian and modified Bessel variations in the core and cladding, respectively, is more accurate in comparison with the Gaussian function over a wide range of values of normalized frequency and aspect ratio. Also, it predicts the propagation characteristics, more accurately, than the Gaussian function from variational and recently reported Marcuse-type formulations. Further, in terms of such range of values, a complete formulation of variational parameter for the Gaussian-modified Bessel function is prescribed for ready reference to the system users to predict the modal field and propagation characteristics **[9]** .

Further, we theoretically investigate the fiber tip based hyperbolic microlens coupling efficiency of circular core trapezoidal index SMF and a laser diode. The corresponding analytical expressions are formulated considering ABCD matrix for hyperbolic microlens following paraxial approximation and also Gaussian field distributions are considered for both the source and the fiber. Here, we study for two different light-emitting wavelengths of practical importance for such fibers. Then, we construct simple empirical formulations to find out the optimum back focal length as function of normalized frequency and aspect ratio of such fibers for optimal excitation of fiber. These handy relations should guide system designer in designing hyperbolic microlens directly on the tip of such fiber carrying the information signal with no need of dependence on rigorous methods to estimate the optimum back focal length **[10]**.

We present simple and complete empirical relations to predict angle of beam divergence in terms of normalized frequency and aspect ratio of a trapezoidal index SMF. This is done for the far field characterization over a long range of normalized frequencies without the calculation of normalized spot sizes. On comparison, we observe an excellent match of our results with exact values establishing the validity of our formulation. The formulation should attract the attention as a simple alternative to the rigorous methods of estimating angle of beam divergence for such fibers. It can be widely used by system users and developers for a much better control over far-field related calculations and experiments **[11]** .

Based on the splice loss analysis between two perfectly aligned single mode step and trapezoidal index fibers, we propose a simple empirical relation of power transmission coefficient (PTC) in terms of normalised frequency and aspect ratio, using a recently reported Marcuse type formulation of spot size for trapezoidal index fiber. The relation is verified, after comparison with standard results from basic equations. Our empirical relation should find wide use by the system users to predict PTC for known opto-geometrical parameters without the knowledge of spot size. Also, a simple graphical technique to predict an unknown aspect ratio of a trapezoidal index fiber is suggested and justified **[14]**.

We use the splice loss measurement technique in absence and presence of angular misalignment and report a simple and accurate method to predict the unknown aspect ratio of a supplied circular core trapezoidal index SMF. We, first, propose to determine the spot size of the unknown fiber from splice between two such fibers with angular misalignment. Then using a known empirical relation of PTC and a graphical technique, we employ this spot size in splice loss between a step index and trapezoidal index fiber in absence of angular misalignment to predict the unknown aspect ratio. The method should find wide use by system developers and system users **[15]**.

In order to predict the unknown aspect ratio of a given single mode trapezoidal index fiber, a simple and straight-forward method is presented. This approach calculates the normalised spot size of such fiber from the measurement of splice loss between two such identical fibers in presence of normalised transverse misalignment. Then, we use this fiber spot size as a test case in splice loss between step index and such fiber in absence of any misalignment to elucidate and justify our technique. The method is shown to predict the unknown aspect ratio of the given fiber using a simple graphical technique and recently available expression of PTC **[16]**.

References of Publications during the Fellowship tenure from 01-04-2016 to 31-03-2018

[1] A.Sadhu and **S.Sarkar** (2016). "A straightforward approximate analysis of Kerr nonlinear processes in sub-wavelength diameter optical fiber with better accuracy over variational technique". *Optics Communications, 367,* 80-85.

[2] A.Sadhu and **S.Sarkar** (2017). "Effect of grading in refractive index profile on Kerr nonlinear optical processes in single-mode sub-wavelength diameter optical fiber using a straightforward method". *Journal of Modern Optics, 64*(2), 156-163.

[3] A.Sadhu and **S.Sarkar** (2016). "Interesting effect of aspect ratio on Kerr nonlinear optical processes in subwavelength diameter single-mode trapezoidal index fiber using Marcuse-type spot-size formulations". *Optical Engineering, 55*(8), 087101-087101.

[4] A.Karak, S. Pramanik and S. **Sarkar** (2016). "Effect of lower and upper parabolic dips in refractive index profile on performance of coaxial fiber Raman gain amplifier". *Optical Engineering, 55*(3), 036103-036103.

[5] P.Ghosh and **S.Sarkar** (2016). "Prospective effect in dispersion properties of photonic crystal fibers by selective water-filling of holes". *Applied optics, 55*(3), 491-497.

[6] P.Ghosh, **S.Sarkar** (2017), "Versatile dispersion characteristics of water solution of glycerine in selective filling of holes in photonic crystal fibers". *Appl. Opt*. 56(10), 2927-2936.

[7] D.Roy and S.**Sarkar** (2016). "Simple but accurate method to compute LP11 mode cutoff frequency of nonlinear optical fibers by Chebyshev technique". *Optical Engineering*, *55*(8), 084105.

[8] A.K.Mallick and **S.Sarkar** (2017). "Aspect ratio based nonlinear effects in spot size dependent propagation characteristics of trapezoidal index single mode fiber". *Optik-International Journal for Light and Electron Optics*, *140*, 205-210.

[9] A.K.Mallick and **S.Sarkar** (2017). "Detailed variational analysis of single mode trapezoidal index fiber involving two simple approximations of fundamental mode with comparison relating accurate prediction of propagation characteristics". *Journal of Modern Optics*, *64*(6), 646-652.

[10] A.K.Mallick, S.Mukhopadhyay and **S.Sarkar** (2016). "Coupling of a laser diode to single mode circular core trapezoidal index fiber via hyperbolic microlens on the fiber tip and construction of empirical relations to determine the optimum back focal length". *Optik-International Journal for Light and Electron Optics*, *127*(23), 11418-11426.

[11] T.Das, J.Sinha, and **S.Sarkar** (2017). "Aspect ratio-based formulation for far-field characterization of single-mode trapezoidal index fibers". *Optical Engineering*, *56*(4), 046106.

[12] S.Chakraborty, D.Roy, S. Mukhopadhyay and **S.Sarkar** (2017). "An investigative study of efficient coupling mechanism of a hemispherical microlens tipped single mode photonic crystal fiber to a laser diode by ABCD matrix formulation and determination of the optimal separation distance". *Optik-International Journal for Light and Electron Optics*, *149*, 81-89.

[13] S.Chakraborty, P.Ghosh and **S.Sarkar** (2018). "Propagation characteristics of some intricate planar waveguides of practical interest by finite difference method". *Optik-International Journal for Light and Electron Optics*, *158*, 15-27.

[14] A.R.Chowdhury, I.Dutta, A.K.Mallick, and **S.Sarkar** (2018). "Prediction of power transmission coefficient and the aspect ratio of a single mode trapezoidal index fiber by using splice loss technique". *Optik-International Journal for Light and Electron Optics* (accepted and to be published)

[15] I. Dutta, D. Kumbhakar and **S.Sarkar** (2018). " Prediction of unknown aspect ratio of a single mode trapezoidal index fiber using splice loss technique considering angular misalignment". *Optik-International Journal for Light and Electron Optics*. (accepted in May, 2018 and to be published).

[16] A.R.Chowdhury, D.Kumbhakar,. and **S.Sarkar** (2018)." Prediction of unknown aspect ratio of a single mode trapezoidal index fiber using splice loss technique considering transverse misalignment". (to be communicated).

[17] T.Das, J.Sinha, and **S.Sarkar** (2018). "Nonlinear effects in aspect ratio based far-field characterization of single-mode trapezoidal index fibers", *Optik-International Journal for Light and Electron Optics, 171, 517-522*

(B) Invited Talks (from 01-04-2016 to 31-03-2018)

DATE	PLACE	TOPIC SPOKEN ON
June,2016	C V Raman Institute of Engineering, Cuttack	1.Gaussian beams in Lasers and Fiber Optics, 2.Photonic Crystal Fiber-concepts and application, 3.Nonlinear Fiber Optics and Solitons
27th November,2016	OSI international symposium. International Conference on Light and Light Based Technologies, 2016 organized by Tezpur University	Modeling and Analyses of Photonic Crystal Fibers and Photonic Nanowires with Some Novel Applications
6th and 7th March, 2017	Cambridge Institute of Technology, Ranchi as Guest of Honour	From Fiber optics to Photonics & Nanophotonics
16th March, 2017	NSHM Knowledge Campus, Durgapur	Concepts of Fiber optics leading to Photonics and Nanophotonics and brief overview of research scenario.

The fellow have been invited to be a member of the T.P.C of the international conference on Fiber Optics and Photonics, PHOTONICS - 18, to be organized by the Department of Physics, I.I.T, Delhi.

(C) Ph.D Thesis Submitted/Awarded (from 01-04-2016 to 31-03- 2018) with Thesis titles

1. Anup Karak (awarded)

2. Dipankar Kundu (submitted before 31-03-2017 and awarded before 31-03-2018)

3. Aswini Kumar Mallick (submitted before 31-03-2018 and awarded in April, 2018)

4. Arunangshu Sadhu (submitted in November, 2017)

5. Prasenjit Ghosh (submitted in April, 2018)

6.Prosenjit Roy Chowdhury (expecting to submit in May, 2018)

The list of Theses in connection with the scheme is given below.

1. Modeling and analysis of non-linear sub-wavelength diameter and conventional single mode fiber - Arunangshu Sadhu (2017)

2. Simulative investigation on propagation characteristics of photonic crystal fibers and planar wave guide structure - Prasenjit Ghosh (2018)

3. Modeling, analysis and propagation characteristics of single mode trapezoidal optical fibers - Aswini Kumar Mallick (2017)

4. Modeling and analysis of photonic crystal fibers - Dipankar Kundu (2016)

5. Propagation characteristics of single mode conventional and photonic crystal linear and nonlinear fibers and fiber Raman gain amplifiers - Anup Karak (2016)

6. Some studies on propagation characteristics of single mode fibers with linear and doped media with emphasis on spot size - Prosenjit Roy Chowdhury (to be submitted shortly)

(D) Departmental collaboration (from 01-04-2016 to 31-03-2018)

The Fellow , during the tenure, also has initiated successful collaborations and is still continuing with the Departmental colleagues, Dr. A. Karmakar (HoD) and Dr. J. Sinha with whom he is guiding two scholars, Mr. Debarup Roy and Mr. Titas Das, respectively.
Mr. Debarup Roy has published one paper (Ref. [7]). He is presently registered with myself being second guide and Dr. Karmakar. He is trying to publish few papers with both of us and is to communicate one or two papers shortly. Mr. Titas Das has only published one paper (Ref. [11]) with Dr. J. Sinha (his first guide) and myself (his co-guide) and has communicated one paper [17].

(E) Future Plan

In the coming years, we will pick up the studies of tellurite based FRGA with comparison to associated conventional characteristics and contribute through publications to enrich this emerging field. Side by side, we will consolidate our matured grasp over principles of SDOF and investigate this field in the context of dispersion-flattened and other interesting profiles to explore maximization of NOP. The study of liquid infiltrated PCF has given us success by publications in Applied Optics. We will consider other liquids to explore whether we can get better ultraflat GVD congenial for SCG. Finally, we will explore other fields of allied research. We are also trying to write books based on our research involving my students with due acknowledgement to UGC in books and papers.

It would have been nice if the promising end of such R & D activities is encouraged with a further extension of one or two years from UGC or through other programs of other Government funding agencies. It is seen that most of the existing fellowships for superannuated professors above 65 like SERB distinguished fellowship etc. are enjoyed mostly by fellows from IITs or IISC or central institutes which are yet to deliver our pre-independent excellence according to the huge funds enjoyed by them, being premier national institutes. I am glad to say that with the support of UGC, I had been able to promote R & D in state level universities.

Submitted by,

Prof. Somenath Sarkar
Formerly UGC Emeritus Fellow
Department of Electronic Science, University of Calcutta