HIGH POWER FIBER LASERS: FUNDAMENTALS TO APPLICATIONS

RANJAN SEN, MAITREYEE SAHA*, SOURAV DAS CHOWDHURY, NISHANT KUMAR SHEKHAR, DEBASIS PAL, ADITI GHOSH, ANIRBAN DHAR, ATASI PAL AND MRINMAY PAL

Some Historical Remarks

The idea of optical communications by transmitting speech through a beam of light is as ancient as 1880 when Alexander Graham Bell had invented the "photophone", shortly after the invention of telephone. With the advent of the laser and LED in the early 1960s, numerous possibilities for practical applications of light-wave communications became apparent. By utilizing only a small part of the visible or infrared radiation frequencies, a single light-wave system could simultaneously carry the telephone conversations of a nationwide population. However, it was realized very soon, unlike the microwave and radio-relay systems, the projection of laser beams through the atmosphere is unrealistic due to inevitable interruptions by atmospheric disturbances like fog, storm, rain, snow etc. So, the main challenge of the optical engineers was to identify an appropriate medium through which light can be transmitted over long distance. In 1966, K. C. Kao and G. A. Hockman of Standard Telecommunications reported, after extensive measurements of different commercially available bulk glass samples, optical fibers can be potential signal transmission medium for long distance communications if absorption and scattering losses can be brought down to below 20 dB/km at operating wavelength by removing impurities of the glass and simultaneously transmitting signals at longer wavelengths[1]. This groundbreaking suggestion stimulated tremendous progress in the development of processing techniques to fabricate light guides which exhibit low attenuation, high bandwidth, good dimensional control and excellent mechanical properties. In order to obtain the light guidance over miles, silica optical fibers were designed in a way that the light should confine into the central part of the fiber and may not leak from the outer surface. Each fiber usually consists of three layers: i) Coating, ii) Clad and iii) Core. The outer layer is a polymer coating to protect environmental hazards. Within the protective coating, the glass fiber itself has a core region with a higher refractive index (RI) than that of its surrounding cladding so that light beams can be transmitted infinitely due to the effect of total internal reflection. In the mid-1960s, various laboratories around the world started to develop significant low loss optical fibers by eliminating impurities such as iron, chromium, vanadium, water etc. The breakthrough came when low loss glass fibers were prepared at Corning Glass Works in 1970 by R. D. Maurer with a loss of 17 dB/km at wavelength of 632.8 µm[2]. A dramatic improvement in process efficiency as well as attenuation was realized in 1974 with the invention of Modified Chemical Vapor Deposition (MCVD) technique by J. B. MacChesney at Bell Lab[3]. Single mode passive silica fibers with losses as low as 0.36 dB/km at 1.3 µm and 0.2 dB/km at 1.55 µm were demonstrated. By early 1980s, this MCVD process had been widely adopted and accounted for the dominant fraction of the optical fiber produced throughout the world. Even at this low loss value, laser beams can only be transmitted over few kilometers after which amplification is needed due to weakening of the input signal. The second breakthrough for the telecommunication industries was realized after designing of Erbium (Er) doped fiber amplifier (EDFA) which provides signal

Fiber Optics and Photonics Division, CSIR–Central Glass & Ceramic Research Institute, 196, Raja S. C. Mullick Road, Kolkata – 700032, India, email: rsen@cgcri.res.in

* Corresponding author; e-mail : maitreyee.cgcri@gmail.com

amplification at the lowest loss window of silica fibers along with large bandwidth and high signal-to-noise ratio (SNR) value. EDFAs found extensive application in all-fiber configuration for easy integration in an optical communication network. But doping rare-earth (RE) ions like Er, ytterbium (Yb), thulium (Tm) etc into the core of the optical fibers was not an easy job due to the unavailability of suitable liquid RE precursors. For this reason, modification in the conventional MCVD process was obvious. Two of the most common techniques developed in this direction are solution doping (SD) method and vapor phase doping (VPD) process. First one was invented by David Payne and co-workers in 1987[4] while the later one was demonstrated by R. P. Tumminelli et al. in 1990[5]. Development of these two process technologies of active fiber fabrication has revolutionized the telecom as well as the material processing industries worldwide in the modern era.

Evolution of Fiber Lasers in Modern Era

Fiber lasers are typically solid state lasers where the gain or active medium is a RE doped optical fiber which is optically pumped by diode lasers. In amorphous silica host, RE ions exhibit large absorption and emission spectra allowing fiber lasers to be operated as continuous wave (CW) and also ultra-short pulses with large wavelength tunability[6,7]. Three prime wavelength regions of operation in fiber laser technology are 1 µm, 1.55 µm and 2 µm, each having its own unique features. Apart from amplifiers Er doped fiber is also used in CW and pulsed laser systems at ~1.55 µm wavelength. Yb doped fiber laser at ~1 µm wavelength region gained its popularity because of its immense applications in material processing industries. It covers more than 90% of the market demand of fiber laser industry in the field of laser cutting, marking, engraving, welding etc. On other hand, Tm doped fiber laser which operates at ~2 µm is fast gaining its popularity as a superior medical laser. Due to high absorption in water, the 2 µm fiber laser system is being used for soft tissue surgery, eye surgery and lithotripsy[7].

Although the first report of the fiber laser was manifested in early 1960s by Snitzer et al., it started its journey into the commercial field in mid-1990s after the invention of cladding pump principle by H. M. Pask et al[8,9]. This fiber laser produced 500 mW of out put power at ~1 µm wavelength with a very high conversion efficiency of 80% with respect to the input pump power. At the end of 1990s, the first 100-watt level laser was developed which was followed by the first kilowatt class laser using a large core double clad Yb doped fiber[10]. The power of the kilowatt laser was limited only by the available pump source. Since all these lasers utilized some free-space components, exploration was on for all-fiber configuration which provides robust, hassle-free operations. Finally in 2009, IPG Photonics Inc. developed and commercialized a single-mode all-fiber laser system with a record power of 10 kW. In addition to this, development of a 100 kW multimode fiber laser was reported at ~1 µm wavelength in 2012 which is the highest ever power from a solid state laser to date[11]. This remarkable advances in fiber laser technology in past two decades have rapidly blown up its market demand around the world, out of which almost 50% of the total market is consolidated in East Asia (viz. China, Japan and India). The advantages of fiber lasers – compactness, high average power, excellent beam quality, longer lifetime, easy handling capability, high efficiency and low maintenance cost – have allowed them to be superior contender against conventional solid–state lasers[12,13]. A significant number of fiber laser based technologies have been commercialized in recent past because of their remarkable impacts in wide application ranges. For last several years fiber laser market has exhibited highest growth among all laser technologies and continuing on that path. As a result, the revenue of fiber laser sales was predicted to touch $1.6 billion in 2015 with an annual growth rate of nearly 25%, capturing 30% of the total market share as forecasted by Strategies Unlimited.

Fundamentals of Fiber Lasers

Fiber lasers are adaptable to many configurations with different output features. A single mode fiber laser can deliver power with excellent beam quality while a multimode fiber laser is capable of delivering much higher power. Often a seed and amplifier based architecture [also called master oscillator power amplifier (MOPA)] is used where a low power fiber based seed source is designed and the power is scaled up using a single stage or multi-stage amplifier. Fig. 1 shows the double clad fiber architecture used in high power fiber lasers. For low power,

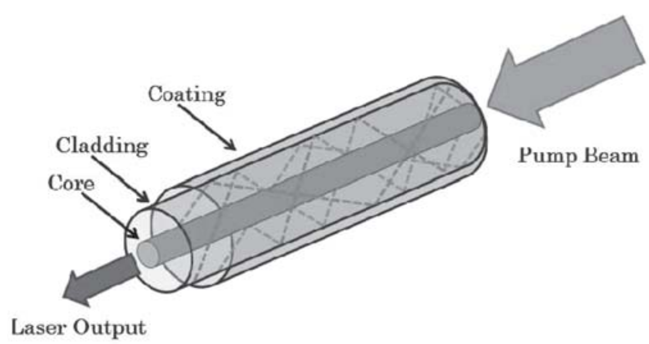

Fig. 1. Double clad fiber structure.

milli-watt scale fiber lasers, pumping is done directly to the core of the doped fiber. On the contrary, for high power, watt to kilo-watt scale fiber lasers, a double clad active fiber is used where the pump is launched into the inner cladding. The inner clad is made for guiding of the pump beam which during propagation crosses the active core and gets absorbed in it. Various noncircular inner clad geometries are used in fiber laser technology like hexagonal, octagonal, single-D, double-D etc. to couple the pump beam into the active core (as shown in Fig. 2)[14, 15].

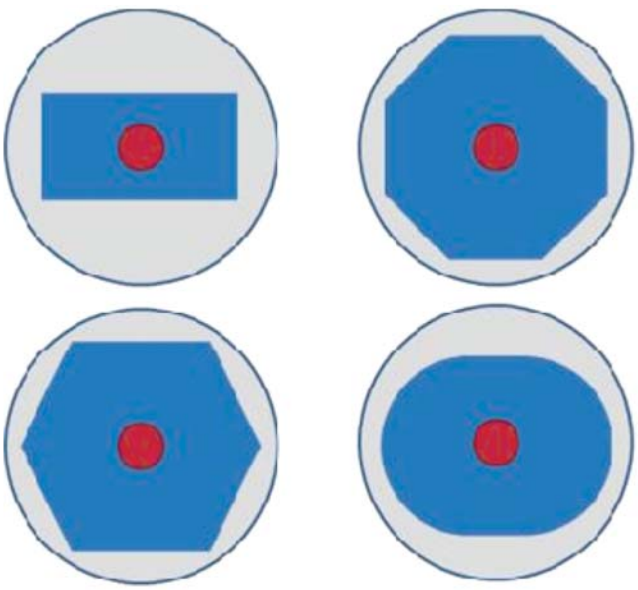

Fig. 2. Different inner cladding (blue region) geometry of double clad fiber.

Fiber laser can also deliver CW or pulsed output depending on the cavity configuration. In hybrid architecture the reflectors, couplers and other passive components are bulk optics which is generally associated with alignment issues while in all-fiber configuration fiber based couplers, fiber Bragg gratings (FBG) as reflectors are directly spliced to the active fiber to design the laser cavity or amplifier making it more rugged for commercialization. A CW fiber laser is formed by simply splicing one high reflecting and one low reflecting FBGs on either side of the active fiber to form the laser cavity.

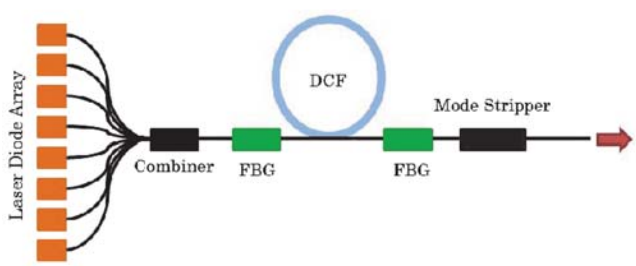

Fig. 3. Schematic of a diode pumped double clad fiber laser in linear or Fabry-Perot configuration.

The cavity can be either in linear or ring configuration as shown in Fig. 3 and 4 respectively. In ring cavity, instead of FBG, a coupler is used to couple out a fraction of power and rest is coupled back into the cavity. In either configuration the pump power is coupled to the fiber core or cladding using couplers or multi-mode pump combiners. In double clad configuration the excess pump power, which flows through the active fiber without interacting with the doped core, is dumped using a cladding mode stripper. The output is taken at the seed output or amplification can be done for further scaling of power (as shown in Fig. 5)[16].

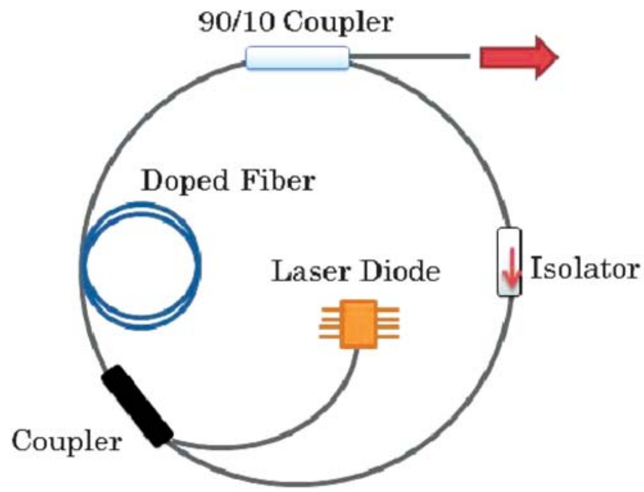

Fig. 4. Schematic of a ring cavity fiber laser.

Pulsed fiber laser is achieved by Q-switching or mode locking or gain switching mechanism. Typically pulses with few ns to hundreds of nano-second duration are generated by Q-switching method. Mode-locking technique is used to generate pulses with ps to fs duration. Gain switching is done by modulating the pump source itself. Depending on parameters like pulse duration, peak power and energy, pulsed fiber lasers are employed in different material processing, non-linear spectroscopy and imaging applications. Thermal management is easier in the fiber lasers due to their high surface-to-volume ratio eradicating the chances of thermal lensing which is a big problem in crystal based laser systems. Another significant factor in fiber laser development is fiber non-linearity[17]. Stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), self-pulsing and mode instabilities limits the attainable output power from a fiber laser system and often leads to system damages. Non-linearity arises due to strong confinement of light in the fiber core. So smaller the core, higher will be the non-linearity. Keeping this in mind high power fiber laser system uses large mode area (LMA) fibers which comprises of large core diameters with comparatively lower RI to put the nonlinearity thresholds high enough so that targeted power levels can be achieved. Along with increasing the gain volume, the LMA fiber also increases the energy storage in the active fibers and by combining multiple laser systems the fiber lasers also reaching to its solid state counterpart in delivering high energy[14,18]. Though nonlinearity is bad for standard laser systems, with care it can be utilized in numerous fields staring from ultra-short pulse generation, large no of new wavelength generation, medical imaging and non-linear spectroscopy [19].

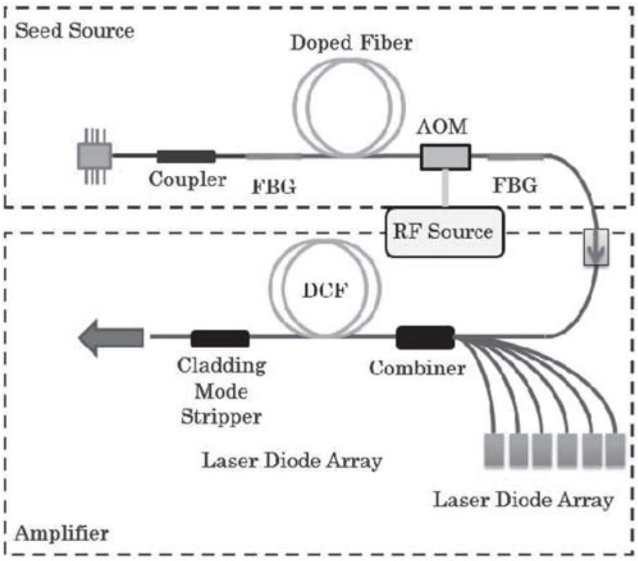

Fig. 5. Q-switched fiber laser seed source further amplified using a double clad fiber amplifier (MOPA configuration).

Fabrication of the RE Doped Active Fibers

For wavelengths below 2.2 μm, silica glasses have proved most successful, owing to their good mechanical and thermal properties and relatively low nonlinearities. But RE oxides are not much soluble in silica matrix and form clusters and defects when doped alone above few ppm levels. For making highly RE doped fibers, co-dopants like phosphorous (P) and/or aluminum (Al) are required at higher concentration to increase RE solubility in the silica matrix[20]. Thus, fabrication of RE doped fibers with varied designs, compositions and appropriate RE concentration attracts a lot of research interest to reduce dopant-rich phase separation, improve compositional homogeneity of RE doped glass and lowering the background losses simultaneously. In order to fabricate the RE doped optical fiber, a glass rod called "Preform" is made whose core is doped with RE ions by utilizing SD or VPD method. Then acrylate polymer coated fiber is drawn from this preform by using a fiber drawing tower.

Till date, SD method is the most popular RE doping technique due to its simple operational scheme and wide range of dopants selectivity. It has been optimized over the years and is now providing the maximum part of the commercially available RE doped fibers. Fabrication of optical preforms by SD method involves three main steps: i) soot layer deposition, ii) solution soaking and iii) consolidation and collapsing. The preform fabrication process starts with the deposition of pure silica sintered cladding layer which is followed by porous core layer of composition SiO_2–GeO_2/ SiO_2– GeO_2–P_2O_5 and then this porous layer is impregnated with alcoholic/water solution of RE and Al salts. Afterwards the tube is dehydrated, sintered and collapsed to form the preform[21]. However, this process suffers from poor repeatability and variation in dopants concentration along the preform length. Moreover, it is difficult to control RI precisely and core diameter cannot be increased beyond a limit which is essential for laser fibers.

On this technological backdrop, VPD process offers several advantages over SD method. In this process, the incorporation of REs and co-dopants occurs simultaneously with the deposition of silica which allows homogeneous dopants distribution in the glass matrix and leads to significantly less RE clustering. In addition, it provides deposition of multiple core layers comprising SiO_2-Al_2O_3-RE_2O_3 in a reproducible manner which results in ~3 times larger core diameter than the SD method. Moreover, as the preform fabrication is carried out under "in-situ" condition, it reduces the chances of contamination (like dust, moisture) which resulted during cutting/soaking/ reinstallation steps involved in SD method. VPD technique is based on high temperature sublimation of solid RE chelate compounds in a closed evaporation system and carrying the generated vapors to the reaction zone with a suitable inert carrier gas along with the other glass forming constituents. The high volatility of the solid RE chelate precursors at moderate temperature ranges evolves sufficient amount of RE ions to be incorporated during core layer formation. The precursor materials while reacting with O_2 at the hot zone of an oxy-hydrogen burner, form sub-micron sized oxide particles which deposit as porous soot layer at the inside wall of the substrate tube. As the burner moves further over the deposited soot layer, consolidation takes place leaving fully sintered transparent glass. Finally, at high temperature the tube is collapsed into solid rod[22].

Fiber Laser at 1 μm

For most industrial and scientific applications, the commonly used high power fiber laser is Yb doped fiber laser. In silica matrix Yb ions exhibit an absorption band of 0.85 – 1 μm and a broad emission band of 0.9 – 1.12 μm. It is most commonly excited with 915, 940 and 976 nm laser diodes. The energy level diagram of Yb^{3+} in silica glass fiber is shown in Fig. 6. At 976 nm pumping, the non-radiative loss is just 9% which made it the most efficient fiber laser till date. After the first demonstration in diode pumped configuration in 1988 by Hanna et al.[23], Yb doped fiber laser has grown enormously in both CW and pulsed domain. Q-switched lasers with pulse duration from few ns to few hundred ns along with pulse energy as high as 10 mJ are now commercially available[24]. Due to large gain bandwidth Yb doped fiber laser has the potential to generate small duration pulses as short as 4.5 fs [13]. The ultra-fast mode-locked laser is used for precise material processing, pump source for new wavelength generation in specialty optical fibers or external crystals. Ultra-fast pulse with very high peak power at 1 µm is used for supercontinuum generation, second and third harmonic generation (532 nm and 355 nm light generation by using nonlinear crystals), mid-infrared (mid-IR) wavelength generation and nonlinear spectroscopy [coherent anti-Stokes Raman spectroscopy (CARS)][19]. In year 2014, Tunnerman et al. has shown record peak power of 3.8 GW for a 500 fs pulse from a chirped pulsed amplifier system using Yb doped fiber[25]. High internal quantum efficiency, broad gain bandwidth and high power scaling capability at lower cost in all-fiber configuration makes Yb fiber lasers an immediate primary choice for a large number of applications.

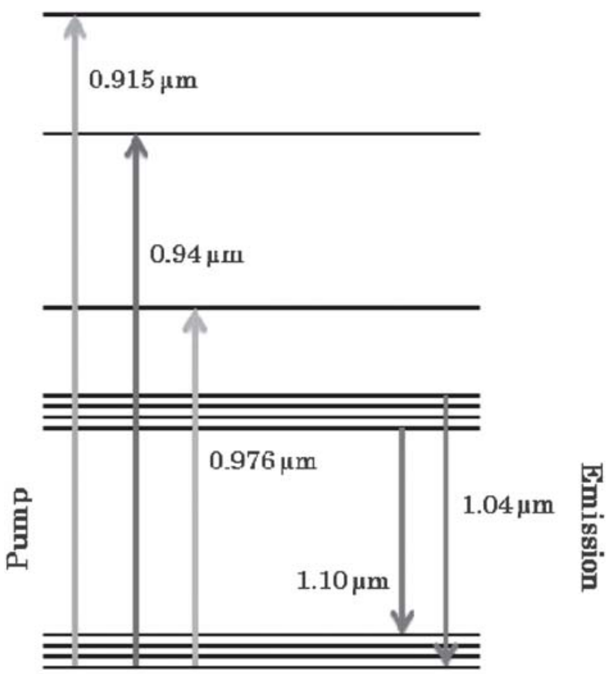

Fig. 6. Energy level diagrams of Yb in silicate glass.

Fiber Laser at 2 µm

Tm doped fiber has broad gain spectra in the range of 1.7 – 2.1 µm under pumping at 0.8 µm and 1.6 µm. Pumping at 0.8 µm can lead to excitation of two Tm^{3+} ions and emit two photons at 2 µm region. Fig. 7 shows the energy level diagram of Tm in silica glass matrix. Moderate to high power Tm doped fiber laser is required for a variety of applications such as medical, material processing, sensing and as pump source for mid-IR operating system. A focused laser with operating wavelength of high water absorption (at around 1.94 µm), can be a good scalpel for soft tissue surgery. A comparative study had been done on CW and pulse Tm doped fiber lasers for ablation of both soft and hard biological tissues [26]. Quasi-CW (QCW) Tm doped fiber lasers are ideal for soft tissue surgery due to the capability of adjusting pulse duration, peak power and repetition rate. The cutting and coagulating properties of the soft tissue also depend on the pulse strength[27]. Both ablation depth and limit of collateral thermal damage on soft tissue are controlled by operational mode of the laser.

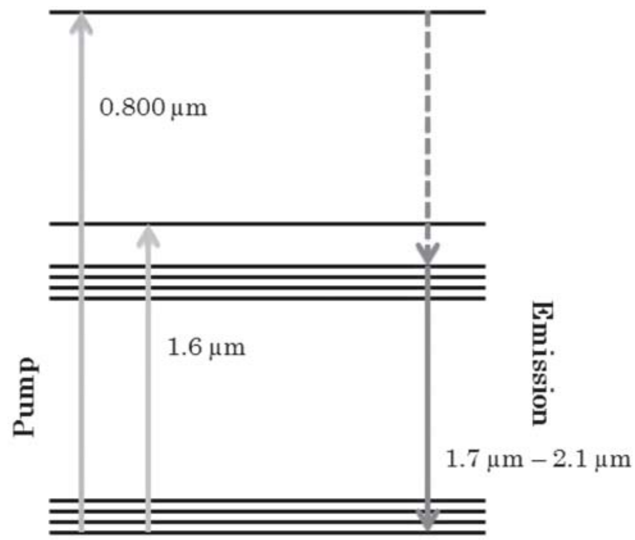

Fig. 7. Energy level diagrams of Tm in silicate glass.

This particular wavelength region is also very applicable towards gas sensing. Numerous molecular absorption bands fall at the 2 µm region which can be exploited for remote sensing of different chemical species by using this Tm doped fiber laser. Apart from medical and sensing applications Tm fiber laser also can be used in LiDAR system. An all-fiber based LiDAR system will be very suitable for airborne and space borne platforms because of its compactness and robustness[28].

Fiber Laser Activity at CGCRI

At CGCRI using state-of-the-art facilities, large core Double clad fibers have been fabricated and used to successfully design and demonstrate fiber lasers at both 1 µm and 2 µm regimes. To fabricate Yb_2O_3 doped preforms

VPD technique is used while for Tm_2O_3 doped preforms SD method is followed. For high average power and high energy applications at 1 µm wavelength, it is necessary to use large core active fibers which also reduce the fiber nonlinearity allowing high power scaling. For this reason, VPD technique is employed to fabricate large core, highly Yb doped preforms. Preforms with length up to 420 mm and diameter of 10.5 – 14.6 mm were fabricated with numerical aperture (NA) in the range of 0.06 – 0.22 for the active fibers. The maximum core diameter achieved in the preform is 4.2 mm while the same is around 40 µm in the fiber of 125 µm diameter. A set of both Tm and Tm/Yb-doped single mode optical fiber in single clad as well as double clad configuration with different host composition and dopant concentrations were designed and fabricated by using the SD method. Both the active fibers with different inner cladding geometries have been fabricated at CGCRI. Fig. 8 shows cross section of the in-house made double-D and hexagonal shaped active fibers.

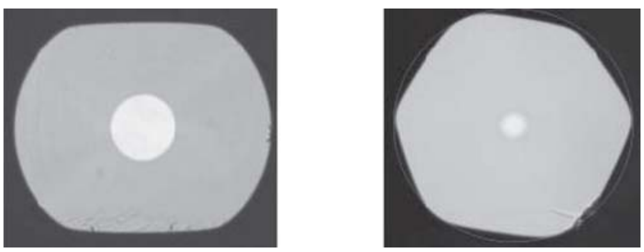

Fig. 8. Double-D and hexagonal shaped inner clad fiber fabricated at CGCRI.

In experiments carried out at IPHT Jena, Germany, fibers of fabricated CGCRI delivered >100 W of CW power at 1064 nm in hybrid fiber laser configuration. Here at CGCRI work is being carried out towards development of novel high power all-fiber laser systems for both CW and pulsed domain aimed towards commercialization. The all-fiber cladding pumped laser using a double-D shaped Yb doped active fiber has been set-up. It is pumped by an array of 6 multi-mode laser diode at 976 nm, each capable of delivering a maximum pump power of 10 W. The pump is coupled to the active fiber via a combiner. The laser cavity was formed by splicing two FBGs on each side of the active fiber. A 99% reflecting FBG and a 20% reflecting FBG as output coupler with 3 nm and 1 nm bandwidth at 1064 nm respectively has been used. An in-house made cladding mode stripper has been used after the output coupler to dump the excess pump power and a 0.5 m long home made passive fiber has been used as delivery fiber. In this configuration, output power of >20 W at 1064 nm has been achieved with linear efficiency of 60% with respect to total pump power (as shown in Fig. 9) which is only limited by the available pump power. An actively Q-switched pulsed fiber laser has been designed for generating high energy pulses with ns duration at 1 µm. An acousto-optic modulator (AOM) has been used to modulate the intra-cavity loss for Q-switching. A three stage set-up consisting of a seed source, pre-amplifier and booster amplifier all using LMA fibers with double clad geometry has been designed. LMA fiber as mentioned before provide low nonlinearity and high saturation energy required for distortion less pulse amplification with high energy, high average power and high peak power. The set-up has been optimized to deliver spectrally and temporally clean Gaussian shaped pulses aiming towards laser marking application. Currently table top experimental set-up delivers 100 ns pulses with repetition rate varying in the range of 10 – 40 kHz along with maximum pulse average power of 12 W and pulse energy of 0.8 mJ (as shown in Fig. 10).

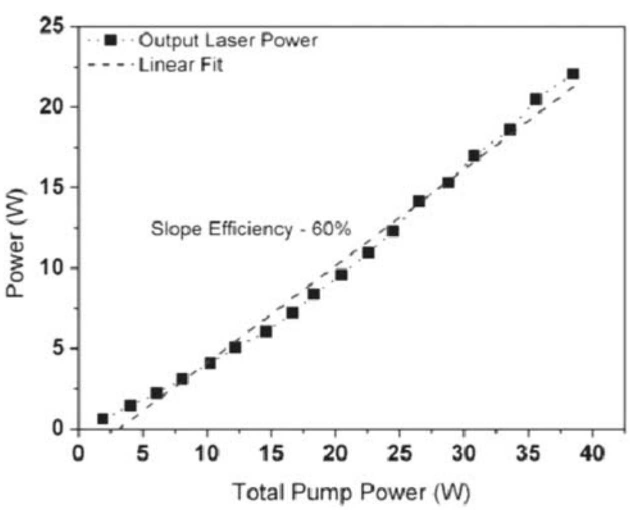

Fig. 9. Lasing characteristics of Yb doped fiber laser designed at CGCRI.

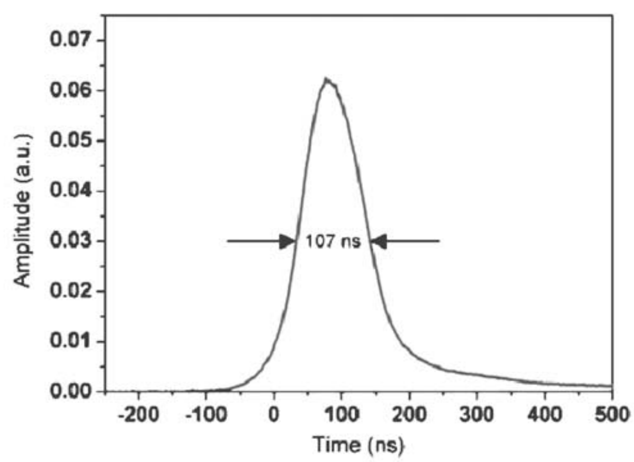

Fig. 10. Temporal shape of the output pulse from the Yb doped Q-switched fiber laser designed at CGCRI.

Targeted towards soft tissue surgery an all-fiber laser at 1874 nm has been designed by using fabricated Tm/Yb co-doped fiber. An Er doped fiber laser at 1600 nm was used as an auxiliary pump source, unidirectional with the standard 980 nm laser diode to excite the Tm/Yb doped fiber laser resonator in order to enhance the Yb to Tm energy transfer. The laser resonators are conveniently tuned by relaxation-compression of the FBG pair in the first laser set-up. Tunability was also achieved by designing a ring laser under 1600 nm pumping with Tm doped fiber (as shown in Fig. 11). The laser wavelength in this filter less configuration can be tuned by introducing an intra-cavity loss. A laser cavity has been set-up under multimode pumping at 808 nm using Tm doped active fiber in double clad configuration to be operated in both CW and QCW mode. In this configuration, six numbers of laser diodes are used through a pump combiner to pump the active fiber. The output power of 7 W has been achieved at 1950 nm till date in CW configuration. In QCW mode, the laser average power is in the range of 0.8 – 4.05 W with pulse width extending from 200 μs to 1 ms. The pulse energy varied in the range of 0.7 – 3.5 mJ. Fig. 12 shows QCW pulse train of 1 ms pulses at 200 Hz repetition rate.

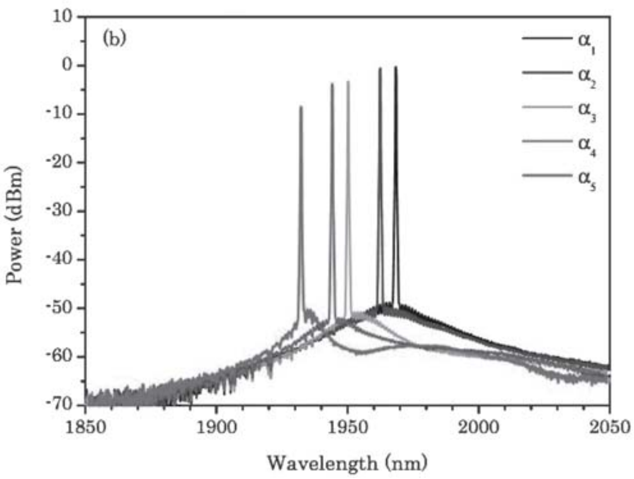

Fig. 11. Tunable laser spectrum in ring cavity from the Tm doped fiber laser designed at CGCRI.

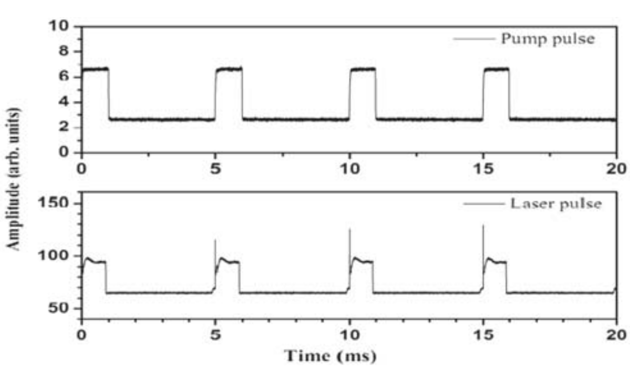

Fig. 12. Pump pulse and laser pulse for 20% duty cycle, 1 ms pulse width and 200 Hz repetition rate.

Conclusion

Although fiber laser technology has developed over the past 50 years, rapid growth has been observed in the last two decades due to fast development of laser diodes, advanced fiber fabrication technology and new pumping techniques. Because of their inherent advantages and attractive properties, fiber lasers have been widely used in a variety of areas. We have given an overview of the CW and pulsed fiber lasers operating at 1 μm and 2 μm wavelengths in view of material processing as well as medical applications. So far, tremendous success of 1 μm fiber lasers has been achieved worldwide. However, moving forward, extending the output beam into the mid-IR wavelength, will be beneficial for a large number of existing or novel applications. The paper also presents a brief review of the on-going research work on fiber laser technology at CSIR–CGCRI starting from the fiber fabrication to the development of laser systems.

Acknowledgements

The authors are thankful to the Director, CSIR–CGCRI and all the members of Fiber Optics and Photonics Division for their continuous support to carry out the work. The authors acknowledge the financial support from GLASSFIB project of Council of Scientific and Industrial Research (CSIR), India and Department of Electronics and Information Technology (DeitY), India. ❐

References

[l] K. C. Kao and G. A. Hockman, *Proc. IEE*, **113** (7), 1151 (1966).

[2] F. P. Kapron, D. B. Keck and R. D. Maurer, *Appl. Phys. Lett.*, **17**, 423 (1970).

[3] J. B. MacChesney, P. B. O'Connor and H. M. Presby, *Proc. IEEE*, **62**, 1278 (1974).

[4] J. E. Townsend, S. B. Poole and D. N. Payne, *Electron. Lett.*, **23** (7), 329 (1987).

[5] R. P. Tumminelli, B. C. McCollum and E. Snitzer, *J. Lightwave Technol.*, **8** (11), 1680 (1990).

[6] J. Kirchhof, *et al.*, *J. Non-Cryst. Solids*, **352**, 2399 (2006).

[7] S. D. Jackson, *et al.*, *Nat. Photon.*, **6**, 423 (2012).

[8] C. J. Koester and E. Snitzer, *Appl. Opt.*, **3** (10), 1182 (1964).

[9] H. M. Pask, *et al.*, *IEEE J. Sel. Topics Quantum Electron*, **1** (1), 2 (1995).

[10] Y. Jeong, *et al.*, *Opt. Express*, **12** (25), 6088 (2004).

[11] V. Fomin, *et al.*, *Laser Optics*, 2014 International Conference.

[12] M. N. Zervas and C. A. Codemard, *IEEE J. Sel. Topics Quantum Electron*, **20**, 219 (2014).

[13] J. Limpert, *et al.*, *IEEE J. Sel. Topics Quantum Electron*, **13**, 537 (1995).

[14] D. J. Richardson, J. Nilsson and W. A. Clarkson, *J. Opt. Soc. Am.* B, **27** (11), B63 (2010).

[15] H. R. Muller, *et al.*, *C. R. Physique*, **7**, 154 (2006).

[16] V. Ter-Mikirtychev, "Fundamentals of Fiber Lasers and Fiber Amplifiers", Springer (2014).

[17] G. P. Agrawal, "Nonlinear Fiber Optics", 5th Edition, Academic Press (2012).

[18] C. Jauregui, *et al.*, *Nat. Photon.*, **7**, 861 (2013).

[19] M. E. Fermann and Ingmar Hartl, "Ultrafast fibre lasers", *Nat. Photon.*, **7**, 868 (2013).

[20] K. Arai, H. Namikawa, K. Kumata and T. Honda, *J. Appl. Phys.*, **59** (10), 3430 (1986).

[21] R. Sen and A. Dhar, "An Improved Method of Fabricating Rare Earth Doped Optical Fiber", in Selected Topics on Optical Fiber Technology, InTech Open Access Publishers, Chapter 3, pp. 73-94 (2012).

[22] M. Saha, *et al.*, *J. Lightwave Technol.*, **33** (17), 3533 (2015).

[23] D. Hanna, R. Percival and I. Perry, *Electron. Lett.*, **24**, 1111 (1988).

[24] http://www.ipgphotonics.com/products_YLPN1-10mJ.htm.

[25] Tino Eidam, *et al.*, *Opt. Express*, **19**, 255 (2011).

[26] F. El-Sherif and T. A. King, *Lasers Med Sci*, **18**, 139 (2003).

[27] A. Heinrich, *et al.*, Proc. of SPIE-OSA Biomedical Optics, **8092**, (2011).

[28] W. Shi, *et al.*, *Appl. Opt.*, **53** (28), 6554 (2014).