Laser wavelength considerations for inscription of Fiber Bragg Gratings: specific to applications in fiber lasers and amplifiers

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Fiber Bragg Gratings (FBGs) have been inscribed using laser wavelengths ranging from 157 nm to 800 nm. Different wavelengths are suitable for inscription of gratings depending on fiber composition. FBGs inscribed by different wavelengths often have different characteristics, namely thermal stability, magnitude of reflectivity and some times even level of spectral purity. Hence, the choice of laser source/ wavelength has to be determined by the intended application of the FBGs. In the current report, we suggest a suitable laser wavelength for inscription of FBGs depending on the intended application, with a particular emphasis on applications in fiber lasers and amplifiers, after extensive review of recent developments.

1. Introduction

FBGs find wide applications as WDM components in telecommunications, as distributed feedback elements, as high reflecting or partial reflecting end mirrors in fiber lasers, as spectral filters, as dispersion compensators (chirped FBGs) and as sensing elements to sense multiple parameters such as temperature, strain, refractive index, liquid level, vacuum, presence of chemicals in ambient etc.

FBG is an in-fiber structure with a periodic variation of refractive index. Due to their growing number of applications and demand, many new fabrication facilities are being added every year for the production and related research and development on FBGs. A fabrication facility for FBGs consists of four main components or inputs, namely 1. laser source for inscription, 2. photosensitive fiber, 3. interference pattern generating set-up or point-by-point inscription set-up and 4. testing and diagnostics set-up. Of all these four components, the laser source is most capital intensive item and hence, due care has to be taken at initial stage of setting up such a facility, in choosing the laser source with appropriate wavelength and other characteristics such as pulse energy density.

Though, there have been two monographs [1] and [2], and a review paper [3], which covered many aspects of FBGs including effects of writing wavelength on inscription of FBGs, many new developments arised such as inscription of gratings using femtosecond UV radiation [4], femtosecond IR radiation [5], further exploration of grating fabrication using second harmonic copper vapor laser [6], observation and /or further development of type IA gratings [7] and chemical composition gratings (CCG) [8]. Further work on development of fiber lasers with integrated FBGs (direct writing of gratings into active medium itself, that is without need for splicing or special geometry for fiber, hydrogenation etc.) [9], [10], took place in past eight years, which necessitated the current report.

FBG is an in-fiber structure with a periodic variation of refractive index. The formation of in-fiber grating structure, for the first time, is observed in germanium (Ge) doped fiber with a 488-nm light from an Ar-ion laser [11]. It has been attributed to the photosensitivity exhibited by the germanosilicate fiber used in the experiment. Photosensitivity refers to permanent change in refractive index of the materials upon exposure to light radiation. The phenomenon, in the current case, has been associated with the presence of GeO_2 in the core of the fiber and associated absorption band located near 5.0 eV, or 242 nm (absorption at 488 nm occurred through a two-photon process). However it may be noted that photosensitivity has also been observed in glasses/ fibers many of which do not contain germanium [12], [2].

An important advance in fabrication of FBGs was made through holographic side exposure technique [13]. This technique allowed formation of FBGs with a Bragg wavelength different from that of inscribing laser. This also allowed fabrication of FBGs using wavelengths, at which fiber has negligible transmission. Consequently, as applications of FBGs grew, many wavelengths ranging from 157 nm to 800 nm are used for fabrication.

Based on the photosensitive mechanism that is responsible for refractive index change, which occur at different energy densities and different cumulative energies, and characteristics of the grating thus formed, FBGs are classified as type I, type IA, type IIA, type II, and CCGs.

Type I FBGs are most commonly observed and refer to FBG formation through monotonic increase in amplitude refractive index (with positive Δn). The index

changes are attributed to erasure and formation of some defects or chemical species within the fiber. The thermal stability of these gratings is usually limited to about 100 $^{\circ}$C [2], though there are exceptions such as type I gratings inscribed in special fibers co-doped with tin, antimony etc., which withstood more than 300 $^{\circ}$C for more than 24 hour exposure with negligible reflectivity loss [14].

Protracted exposure of type I gratings, usually in cases of high GeO$_2$ fibers (>25 mol%, high NA), results in complete or partial erasure of the grating, followed by new spectral formation associated with highly negative Δn (for cumulative fluence exceeding 500 J/cm^2), which is referred as type IIA grating. The index modulation, in this case is associated with structural change of glass due to compaction. These gratings typically show increased level of thermal stability and are stable up to about 300 $^{\circ}$C. There are also type IIA gratings written in special fibers such as nitrogen doped silica fiber, which withstand temperature of up to 1000 $^{\circ}$C.

Type II gratings are observed at energy levels of >1000 mJ/cm^2, usually requiring a single excimer pulse. The index changes are estimated to be of the order of 10^{-2} and are attributed to physical damage limited to fiber core clad interface. Experimental evidence on the formation of these gratings may be found in literature [15]. These gratings offer highest thermal stability of up to 800 $^{\circ}$C. These gratings couple radiation into cladding modes at shorter wavelengths and consequently the transmission spectrum is not as good as it is for other types of FBGs.

Type IA gratings [7], are observed only in hydrogenated germanosilicate fibers, and are formed after erasure of type I gratings. But unlike type IIA gratings, type IA gratings are characterized by large (~18 nm) red shift in Bragg wavelength, which indicated large increase in mean refractive index change, and reduced temperature coefficient (~0.55% of other types of FBGs) [16].

In CCGs, the refractive-index modulation is caused by periodic change in the concentration of one or several dopants in the core of the fiber [Fokine, 2002]. One method for creating a variation in chemical composition is to change the diffusion properties of dopants locally by utilizing periodically induced chemical reactions to modify the bond structure in the glass. This modification can be achieved with good spatial resolution (~0.2 μm) if UV photons are involved in the process. The UV written grating is then 'developed' by exposing briefly to high temperature, which causes diffusion of these modified dopants from the grating region of core, resulting in much higher refractive index modulation with high temperature thermal stability [17], [18], [19]. The thermal stability of such gratings, referred to as chemical composition gratings (CCGs), is limited by the diffusion properties of the modulated dopant. CCGs, which do not rely primarily on defects and trapped charges, have useful properties including stability at temperatures of up to 1000 °C, which is highest thermal stability/operating point among all FBGs.

2. Fiber materials (Writing Medium)

Silica due to its wide abundance in nature, high transmission at visible-IR wavelengths and possibility of drawing into thin fibers over kilometers of length became material of choice for manufacture of optical fibers. However doping of some sort is required in base material fiber to facilitate refractive index difference between central core and surrounding cladding, which is primary guiding mechanism of light in the fiber. The properties of fiber such as attenuation, numerical aperture, photosensitivity etc., are primarily controlled by host material and concentration and type of dopant. FBG inscription or photoinduced refractive index changes are observed in the following types of fibers.

Ge doped silica fibers: It may be noted that Ge is dopant, by default, in the core of many fibers (particularly those used in telecommunications), as a means of achieving core-clad refractive index difference. Consequently, with initial observation of FBG in a Ge doped silica fiber most of the work on fabrication of FBGs took place with Ge doped silica fibers and with inscription wavelengths in and around 240 nm band. Special fibers were developed with high Germanium doping to enhance photosensitivity in this band. Photosensitivity in Ge doped fibers has also been enhanced using techniques such as hydrogen loading in to the fibers [1]. These fibers are suitable for most of the applications in telecommunications and fiber sensors. The GeO$_2$-SiO$_2$ glass has absorption bands with maxima located at 185 nm, 242 nm and 325 nm where the 185 nm peak is attributed to GeO$_2$ and other two peaks to GeO in Silica [20]. Photosensitivity in these fibers is often characterized by the absorption band at 242 nm, which is associated with the concentration of germanium–oxygen-deficient centers (GODCs) [21]. Strong grating formation was reported using 193nm radiation in germanium-doped fiber in which the germanium– oxygen-deficient center had been eliminated by special perform manufacturing [22]. Grating formation in this fiber was attributed to a two-photon mediated process, whereas in the presence of germanium–oxygen-deficient centers the process was shown to be one-photon mediated [21].

Typical Ge content varies from 3-5 mol% for standard telecommunications fibers (SMF-28) to up to 20 mol% for specially doped fibers to enhance photosensitivity as the number of GeO defects increase with Ge concentration [11]. However, increasing Ge concentration alone to increase photosensitivity is disadvantageous, as it increases numerical aperture (NA) of the fiber, thereby making high Ge silica fibers incompatible with most of low NA communication grade fibers.

Boron-Ge doped fibers: Boron co-doping allows higher doping of Ge (which results in increased photosensitivity, reduced inscription time and large index modulation) without increase in core-clad index difference, hence making the fiber highly photosensitive yet with a desired index profile and NA, which makes the fiber compatible with any other fiber such as small-core large NA fiber amplifiers, standard telecommunications

fibers etc. Boron co-doping introduces about 0.1 dB/m loss at 1550 nm region, also results in increased stress and consequently increased birefringence [1]. It was found that the resulting gratings in these fibers have poorer thermal stability compared to those inscribed in germanosilicate fibers [Brambilla et al. 2001].

Tin doped silica fibers: The primary advantage of Tin (Sn) co-doping is that gratings formed in these fibers survive higher temperatures compared to Boron co-doped fibers. No additional loss in 1550 nm region is introduced as in Boron co-doped fibers. In addition $Sn-SiO_2$ (no germania) fibers show a shift in absorption peak from 242nm (for $GeO_2 - SiO_2$) to 252 nm, and excellent thermal stability of up to ~600 ^{o}C, with a sharp decay of grating strength from thereof to zero at 800 ^{o}C [1]. This thermal behavior of gratings in these fibers is better suitable for operation in high temperature environments, than that of gratings written in germanosilicate fibers as the latter shows a weaker decay that starts at around 200 ^{o}C, and reaches to zero (the grating strength) at 800 ^{o}C [23].

Antimony-Ge doped fibers: These fibers offer good photosensitivity as well as high thermal sustainability for FBGs. FBGs written in these fibers showed thermal sustainability at 900 ^{o}C [14]. These fibers showed better and higher temperature sustainability than those written tin co-doped germanosilicate fibers.

Nitrogen doped silica fibers: Nitrogen doping even in very low quantities results in significant increase in refractive index of silica. Substitution of mere 1% of oxygen atoms by nitrogen atoms in a glass network leads to an increase in the glass refractive index by 0.015 [24]. These fibers are fabricated by the surface plasma CVD process, as usual fiber perform technologies such as MCVD process are not suitable for this fiber. The very low quantity of N doping without need for other dopants makes the properties of N-doped silica fiber close to that of pure silica fiber.

These fibers exhibit moderate to high photosensitivity and allow inscription of type IIA gratings which withstood several hours exposures to temperatures above 900°C with negligible loss of reflectivity [25] Type IIA grating formation in N-doped silica-core fibers is explained by the photo-enhanced diffusion of nitrogen to the cladding region resulting in periodic modulation of the nitrogen concentration along the fiber, thus forming a geometrical structure responsible for type IIa grating growth [26].

Pure silica fibers: In these fibers, core is made up of pure silica and necessary refractive index difference (NA) is usually achieved by reducing the refractive index of cladding with suitable dopant such as fluorine, boron etc., In a new class of fibers known as micro structure fibers or holey fibers the refractive index difference is achieved by appropriately designed air-silica structure. These fibers, because of pure silica core are suitable for applications in radiation environments. In addition holey fibers due to their special properties such as end less single mode operation, large non-linearity etc., find wide applications.

Fluoride fibers: Flouride glass due to their low phonon energy provide extended IR transmission range and result in increased life time of meta stable states compared silica [27]. Therefore, fluoride glasses play a significant role than silica based glasses as a host material for fiber laser applications at IR wavelengths.

Sapphire fibers: The melting point of sapphire (~2050° C) is much higher than transition temperature of silica (~1050 ^{o}C, at which total erasure of even type II FBGs in silica fibers has been observed) and hence FBGs inscribed in this fiber are suitable for high temperature applications [28].

Rare earth ion doped fibers: these fibers are used as active medium for fiber amplifiers and fiber lasers. Suitable rare earth ion such as Yb for 1.08 μm operation, Er for 1.55 μm operation, Tm for 2um operation etc are chosen as dopants. Due to special problems associated with rare earth ion doping and consequent fiber laser/ amplifier operation, requirement special co-dopants such as aluminum, absence of usual doping materials such as germanium, even choosing special host material such as phosphate glass in place of usual silica glass, are sometimes necessary, which in-turn necessitates adoption of special inscription wavelengths, special fiber geometries, for fabrication of FBG in these fibers. These issues are further discussed in later section of the report.

Polymer fibers: Polymer fibers are attractive due to their cost effectiveness for applications involving data communication in local area networks, LED based illumination etc., in 400-800 nm region. Further due to biocompatibility of polymers such as PMMA and possibility of sterilization by gamma radiation makes these fibers attractive for medical applications. In addition, the small Young's modulus and high elastic limit of these materials allow FBGs written in these fibers to offer higher sensitivity and dynamic range for strain monitoring and long range tunability of Bragg wavelength under tension as compared to the FBGs inscribed in silica fibers. PMMA is most popular material for polymer optical fibers where the required refractive index difference between core and clad is usually achieved by using pure PMMA for core and fluorinated PMMA for cladding of the fiber.

3. Laser as a writing source

A simple comparison on the efficacy of laser wavelength for fabrication of FBGs is made difficult by the facts that a) FBGs are inscribed in fibers with different material composition and different doping concentrations, b) Lasers used in the experiments have different coherence characteristics, thereby affecting the depth of modulation of refractive index, c) FBGs are inscribed in different regimes, namely, at different energy densities, which as briefly introduced earlier leads to grating formation through different routes such as color center formation, compaction of glass structure etc. Hence, it is not always possible to predict observable refractive index modulation or explain observed index differences based on mere comparison of absorption coefficients at various wavelengths. Table 1 summarizes the results of photosensitivity at various wavelengths.

Table 1. Typical photosensitive refractive index change observed at various wavelengths.

λ_w (nm)	E (kJ/cm^2) (total fluence) typical	Δn (x 10^{-4}) or reflectivity (%) typical	Fiber/ Material	Reference
157	4.5	1.8	SMF-28	29
193	33	9.1	SMF-28	30
193	7.8	4	Silica fiber (8mol%GeO$_2$)	30
193	137	2.4	Pure silica PCF	31
193	2.4	2	phosphosilicate fiber #H	32
193	1.4	0.8	phosphate glass fiber	33
193	10	2.5	nitrosilicate fiber	24
193	1.4	1.75	FZA fiber	27
193	1	7.8	Sulphur-chlorine doped silica	34
193	1	2	Silica fiber (4.5mol% Ge)	34
213*p	3	4	Nufern GF1B	35
240	9	12	STF	36
242	0.65	2.5	Silica fiber (8mol%GeO$_2$)	37
244cw	-	4.65***	silica fiber (B-Ge) #H	38
248	2 x 10^{-3} *	~100%	silica fiber (15mol% GeO$_2$)	39
248	21	2.8	silica fiber (1mol% SnO$_2$)	23
248	2	-2.7**	silica glass(24mol% SnO$_2$)	40
248	0.6	2	HNLF, make OFS Denmark	41
248	7	4	Fibercore PS1250/1500	42
248*f	0.2	4	Fibercore PS 1250/1500	43
248*f	2.5	-5**	Fibercore PS 1250/1500	43
248*f	0.5	4	Silica fiber (15mol% GeO$_2$)	43
248*f	3.6	-2.5**	Silica fiber (15mol% GeO$_2$)	43
255	2.4	5	SMF28 #H	6
255	22	7	NufernGF1A	6
255	3.2	1.1	Nufern GF4	6
255	42	-1.5**	Nufern GF4	6
255	6	7	FiberCore1250/1550	6
255	90	2.3	SPS fiber(1mol% SnO$_2$)	44
255	90	1.4	Silica fiber (0.2mol% SnO$_2$)	44
264*f	5	2	HNLF, make OFS Denmark	41
264*f	1	25	SMF-28 #H	42
264*f	3	10	Fibercore PS1250/1500	42
264*f	4.5	4	Nufern GF1	42
264*f	0.3	10	NufernGF1 #H	42
266	35	82.6%	SMF-28 #H	45
266cw	435	4	Silica fiber (24mol% GeO$_2$)	46
267*f	58	13	SMF-28	47
267*f	50	0.1	Pure silica fiber	47
267*f	0.62	35	Silica fiber (12mol% P$_2$O$_5$) #H	47
334cw	250	1	Silica fiber (30mol% GeO$_2$)	48
800*f	31680	99.99%	SMF-28	49
800*f	15.3	8dB****	Sapphire fiber	28
800*f	529412	98.7%	aluminosilicate Er-doped fiber	9
800*f	17000	8	ZBLAN fiber	50

FZA fiber: fluorozircoaluminate fiber
SMF-28: standard telecommunications fiber (STF) typically contains 3 mol% germanium in the silica core
PCF: photonic crystal fiber/ air/silica micro structured fiber
Fiber Core 1250/1500-Boron, germanium doped silica fiber
SPS: phosphosilicate fiber
#H :hydrogenated fiber   *f: femtosecond radiation
*p: picosecond radiation   cw: continuous working
At all others wavelengths, the lasers have pulse widths in nanosecond regime
*:typeII (single pulse exposure) grating   **:type IIA grating
***: typeIA grating
****: difference in reflectivity peak and baseline

From the Table 1, some useful observations can be made on the suitability of laser source for inscription of FBGs for different applications. For example, to form FBGs for telecommunications, the writing medium of choice is standard telecommunication fiber and choice of writing wavelengths is wide. F_2 laser at 157 nm, ArF laser at 193 nm, or femtosecond Ti: sapphire laser at 800 nm or its third harmonic at 267 nm, can be used as all these lasers allow writing FBGs with large Δn, in these fibers without hydrogenation.

For the fabrication of FBGs for technology demonstration or for using as sensor elements for temperature and or strain, many laser sources in mid-UV region such as 248 nm (KrF laser), 244 nm (frequency doubled Ar ion laser), 255 nm (frequency doubled Copper vapor laser), or 266 nm (4th harmonic of Nd:YAG) may be used as writing wavelength. Use of these wavelengths to inscribe type I or type IIA FBGs, makes it mandatory to choose either high Ge concentration germanosilicate fibers, or hydrogenated low Ge concentration fibers such as standard telecommunication fiber, as a writing medium. However, high energy pulses (~1J/cm^2) available with KrF excimer laser (~1 J/cm^2) allows inscription of type II FBGs even in telecommunication grade fibers without any sensitization technique.

From Table 1, it is also clear that optimum wavelength for FBG fabrication depends on fiber composition. Because the intended application of FBGs governs the choice of writing medium, as seen in section 2, the optimum wavelength for inscription of FBGs ultimately has to be decided by the intended application of FBGs.

4. Optimum wavelength for inscription of FBGs for applications in fiber lasers

An optical fiber with rare earth ion doped core, when pumped with radiation of a certain wavelength, emits radiation at wavelengths different from that of the pump radiation. This occurs due to the absorption of the pump energy and subsequent emission by rare earth ions. This property of the rare earth ion has been utilized in making fiber lasers and amplifiers. Laser transitions are achieved over a wide range of wavelengths by incorporating an appropriate choice of rare earth dopants into host glass composition. A variety of rare earth ions including Nd, Er, Yb, Ho, Pr, Eu, Ce, Dy, Sm, Tb, Gd, Pm and Tm have been shown to provide useful laser action.

In these fibers, in addition to the rare earth ion doping, usually suitable codopant element is used to promote the solubility of the rare earth element or to modify the phonon energy of the silica host or to broaden the choice of pump source (as in case of Yb/Er system), or for easy fabrication. For example, phosphorus, even in low concentrations (~0.1%), in the form of P_2O_5 in silica, considerably reduces the melting point of glass thereby facilitating easy fabrication of fiber. Though, highly P_2O_5-doped single-mode fibers usually demonstrate relatively high optical losses of 24 dB/km in the 1.1 - 1.5-mm

spectral region, by decreasing the drawing temperature and codoping the phosphosilicate core with fluorine reduction of optical losses is usually achieved in highly P_2O_5-doped fibers [51].

Germanosilicate glasses, while having the merit of photosensitive, are particularly prone to ion clustering (in cases of high concentrations), which results in degradation in efficiency and give rise to instabilities in the laser [52]. In particular it reduces the emission bandwidth of the Er3+ ions and limits the concentrations of Er3+ ions that can be reliably achieved relative to other more established glass hosts such as aluminosilicate [53]

The usual codopant germanium is thus replaced by aluminum in rare earth doped silica fibers, as the latter reduces the tendency of rare earth ions to form clusters at high concentrations [1]. In Yb/Er laser/amplifier systems, phosphosilicate glass is preferred over germanosilicate glass, as the former reduces back transfer rate from Er to Yb and result in better efficiency [54]. Ge codoping in aluminosilicate and phosphosilicate fibers in high concentrations is difficult to achieve, and consequently the photosensitivity is lowered in these fibers [9].

When using other sensitization techniques such as high-pressure low temperature hydrogen loading, only a small subset of Er, Nd, Ce, and Tb doped silicate fibers show reasonable photosensitivity [3], [9]. Hydrogenation also brings in associated problems such as requirement of high pressure chamber (typically 100 atm) and related safety issues, out-diffusion of hydrogen and loss of photosensitivity where the hydrogenated fiber is not UV-presensitized or exposed to write grating immediately after taking from the chamber etc. [55, 56].

The commonly used fiber geometry for high power operation of fiber lasers in 1 μm region is yttrium or neodymium doped double cladding fiber. Usually, the fiber consists of a rare-earth doped core of ~10μm diameter, inner cladding with a typical diameter of 200um (compared to usual 125 μm cladding diameter of single mode photosensitive fibers) and a outer cladding of 400um diameter. Radiation from pump laser is mostly coupled from ends of fiber into inner clad from there into core region, which is gradually absorbed by the core region along the length of the fiber (fraction of radiation which is directly coupled into core region from the pump beam is negligible). The outer cladding is made up of either low index polymer for low power applications or doped silica for high power applications.

Now, it is clear that geometry and composition of the fibers, which are used in fiber lasers and amplifiers are optimized in terms of better operation of laser/amplifier systems rather than from photosensitivity considerations. So, the possible approaches to integrate FBGs with fiber lasers and amplifiers are:

1. Inscription of FBGs in a traditional photosensitive fiber (Ge doped/ Ge doped hydrogenated) and then splicing it to the rare earth doped fiber of fiber amplifier/ laser. Many workers have used this approach in the past, due to lack of alternative methods Currently, double clad germanosilicate fibers, that are splice-compatible to rare

earth doped fibers are available [eg., 57]. However, still some special applications, such as simultaneous multi-wavelength operation, where it may require that a section of fiber containing FBG needs to be different from remaining part of fiber constituting active medium of fiber laser, use this approach [58].

2. Another approach is to use a rare earth doped fibers with special geometry, whereby a B-Ge doped photosensitive annular region was introduced between rare earth doped phosphosilicate core and normal cladding [59]. It was found that though the grating was not in the core of the fiber, the core mode sufficiently overlapped the grating contained annular region.

These two approaches allow use of almost any of laser sources of mentioned in section 3, as one can always choose a fiber, which has either intrinsic photosensitivity or enhanced photosensitivity through sensitization methods such as H_2 loading, flame brushing etc., at irradiation wavelength. However intra-cavity splice losses, loss of fiber strength at splicing joints, are the issues to be addressed in first approach whereas requirement of special geometry for the fiber, for different core dopants as required by the operation of laser/amplifier at desired wavelength, is a hindrance in second approach.

The third approach consists of inscription of FBGs in the active medium of fiber laser itself to alleviate problems mentioned above.

F_2 excimer laser, has been initially used for studying photosensitivity of germanosilicate fibers as well as for photosensitivity lock-in of H_2 loaded SMF-28 fibers [60]. Type II grating formation should be possible in rare earth doped silicate fibers due to proximity of this wavelength to the absorption edge of fused silica. However, due to large cladding diameters of double clad fibers, absorption of laser radiation in cladding has to be considered for inscription of gratings into these fibers using VUV radiation. Unless this problem is addressed, F_2 laser, due to high absorption of 157 nm in silica cladding, may not be suitable to inscribe FBGs in double clad fibers. The absorption coefficient of pure silica is ~61 cm^{-1} [29]. It may be noted that this value is measured for fiber optimized for high transmission at NIR region; that is with low OH concentration (in contrast with fiber optimized for high UV transmission which have large OH concentration). It shows, after taking into surface reflection losses for diametrical ray in circular clad geometry, that ~ 64% of energy incident on fiber reaches the core for 125 μm cladding diameter fiber, which was found sufficient to inscribe FBGs in single mode fibers. However, for a fiber with outer cladding diameter of 400 um only ~28% of total power incident on fiber reaches fiber core, which may not be sufficient for inscription of gratings in the core. Worse still, it may cause grating formation either in inner cladding or core-inner cladding interface.

However, fluorine doping of silica, in addition to decreasing refractive index, also leads to drastic decrease in absorption at VUV wavelengths. Doping concentration and glass fictive temperature were shown to affect the magnitude of absorption [61]. It was shown that increase in fluorine concentration results in blue shift of absorption edge located at 160 nm in fused silica. The measured transmission for 2mm thick fluorine doped silica was ~80%. So double clad fibers are to be specially tailored so that cladding is suitable for grating writing with 157 nm. Though, Photosensitivity of highly phosphorus-doped fibers under 157-nm laser irradiation have been found to be much stronger as compared to 193-nm irradiation [62], conclusive experimental data is not available on grating writing with this wavelength, in fibers, which are optimized for fiber laser/ amplifier operation.

The F_2 laser, due to location of wavelength in VUV, requires special optics made from materials such as MgF_2, LiF, CaF_2 for inscription of FBGs. Also, purging of entire beampath with inert gases is required, which rules out on-line alignment/adjustments of optical, opto-mechanical components without help of remote controls, thereby increasing the complexity of the inscription set-up based on this laser.

ArF laser operating at 193nm has been used to write FBGs in pure silica fibers, phosphate fibers and fluoride fibers (FZA fibers) without help of any sensitization techniques such as hydrogenation. Hence it should be possible to apply this laser to fabricate FBGs in rare earth doped fibers as silicates or phosphates are host material for fibers used in most of fiber laser/amplifiers. The complexity of operation as described earlier for F_2 laser is applicable to this laser too.

Argon ion lasers at mid and near UV wavelengths, because of small CW power (typically few tens of mWs), require large writing times. Type IIA grating formation is highly impracticable for the same reason. Photoinduced gratings could not be observed (refractive index changes at 1330 nm, if any, were estimated to be less than 2×10^{-5}) in hydrogenated cerium doped aluminosilicate fibers at this wavelength as well as at other wavelengths in 200-300nm region generated by this laser, for the same reason [63]. This laser source is suitable for interferometer writing of gratings in germanosilicate fibers due to its large coherence length, good beam quality.

Copper vapor laser because of its high repetition rate and high average power at low pulse energy densities, is suitable for mass fabrication of FBGs [64]. Good coherence characteristics (spatial coherence extending to >60% of beam diameter and 40mm of temporal coherence) of this laser provides choice of wide verity of inscription methods such as biprism [65,66], multiple mirror interferometer, without restricting one to phasemask method. Further, due to possibility of configuring the laser system to yield multiple wavelengths (255nm, 271nm, 289 nm, all of which have been used to inscribe FBGs [67]), the longer wavelength at 289 nm can be used to strip the polymer of the fiber and shorter wavelength to inscribe FBGs [68]. However, due to degradation of mechanical strength of FBGs inscribed at long wavelengths (in 240 nm band) [69], limitation of requiring high Ge doped fibers (or hydrogenation in low Ge doping cases fibers and thereby bringing related problems of hydrogenation), and complete ruling-out of formation of type II gratings due to

small pulse energy density, this laser finds limited use in inscription of FBGs for diverse applications.

Lasers in mid UV region (~240 nm) and near UV region (330 nm), in general, require either high concentrations of germanium or hydrogenation and may not be suitable for inscription of gratings in fibers which are optimized for fiber laser/ amplifier operation [70]. However, possibility of inscription of gratings by type II photosensitivity mechanism in non-germanosilicate fibers with high pulse energy KrF lasers exists, though the transmissionspectrum quality of gratings thus formed may be a concern in some applications [1]. UV lasers with femtosecond pulse widths, should be useful in grating inscription for fiber laser applications through multiphoton absorption mechanism. However, in the absence of direct experimental evidence on inscription of high reflectivity gratings in fibers optimized for fiber laser applications, further exploration in this direction is required.

The IR radiation of Ti:Sapphire laser with femtosecond pulse widths has been recently used to inscribe gratings through type II photosensitivity mechanism. However, two problems arise in using this laser for grating inscription [71]. 1. The large spectral content causes broad dispersion when using phasemask method. 2. The short temporal coherence length (~36μm for 120fs pulsewidth) of these lasers make interferometer based systems nontrivial to align, thereby disallowing most popular and convenient inscription method to tune Bragg wavelength of gratings during inscription. The first problem has been bypassed by using phasemasks with a period, which is larger than the inscription wavelength [71]. The tuning of Bragg wavelength during inscription can be achieved by employing single pulse inscription of each period of grating and point-by-point inscription method simultaneously [72].

Almost all materials used to make optical fibers, are highly transparent to 800 nm radiation. However, at tera watt power density levels, multiphoton excitation mechanism sets-in, thereby inducing refractive index changes through type II photosensitivity mechanism. The multiphoton absorption being intensity dependent, refractive index modification can be made highly localized in very small area which is much smaller than core of the fiber [73], which allows inscription of FBGs with clean transmission spectrum unlike those inscribed with single pulse excimer laser. This laser seems to be most suitable for inscription FBGs, particularly in fibers, which are optimized for operation of fiber lasers and amplifiers for the following lasers.

1. Experimental evidence of inscription of FBGs in fibers, which are optimized for fiber laser operation and consequent fiber laser operation, is available [10].

2. The inscription method does not need special materials like the case of UV lasers (such as F_2 excimer laser) as the wavelength is situated in NIR region.

3. Tuning of Bragg wavelength can be accomplished through point-by-point inscription method.

4. It is possible to inscribe gratings through fiber coating (without employing special coatings as was done earlier, [74]) with related advantages [72].

5. Fast writing time: Typically this laser operates at 1000Hz.With each pulse responsible for one period of grating, a second order grating with Bragg wavelength in 1550 nm needs 1 second of time per 1mm of grating length [75]. The reported inscription times to attain high reflectivity gratings in rare earth doped fibers using phasemask method are about 10 minutes.

6. The refractive index modulation is induced through type II mechanism, hence the resultant FBGs are suitable to high temperature applications. For the same reason, FBGs can be inscribed in wide variety of fibers (with different composition, each of which is tailored for specific applications such as high radiation environment etc.).

7. Further, using a third or higher harmonic generating modules, which are commercially available, the source can be converted into mid UV or deep UV source to inscribe gratings [47].

5. Conclusion

We have presented recent developments in inscription of FBGs using different laser wavelengths. Information on various types of FBGs, typical composition of optical fibers used for the inscription of FBGs, used in the fiber lasers and amplifiers is provided. Possible approaches of integrating FBGs in fiber laser/ amplifier systems are reviewed. Finally based on existing knowledge available in public domain, we have suggested laser source for inscription of FBGs for fiber lasers and amplifiers.

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