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Glasses for Photonic Technologies

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Abstract In the given review, optical transoceanic or transcontinental telecommunication system, as the core of the modern information technology, has been taken into consideration as a model to explain the function of glasses in photonic devices. A comprehensive summary review for glass in optical fiber, laser, laser amplifier, fiber Bragg gratings, optical switching, optical power limiters, optical insulators and acousto-optic modulators is presented.

Keywords Glass, Photonics devices, Optical communication

1. Introduction

The use of semiconductors rather than metals gave the opportunity to build up digital devices which were capable to produce, transfer and record data in digital manner instead of analog. With the invention of lasers in 1960 and glass optical fiber in 1970,s a glass-based revolution in the world of telecommunication has occurred. In such dielectric-based technology, photonic glassy devices using photon instead of electrons were employed to establish the global internet network.

Since photon propagation speed (~10^{10} cm/s) while electron propagation speed (~10^{8} cm/s), therefore, photonic devices have very short time response and super-high information capacity for a single channel. In era of tera-information capacity Tb (10^{12} bits); information density in Tb/cm^2, transportation, storage, display and calculation in Tb/s, super-high frequency processing (modulation, switching, cross-exchanging, coding and decoding) in THz (ps time response) are required. Glasses are promising materials for photonic industry such as lasers, optical fibers, ultrafast optical switches, power limiters, real time holography and others[1–8]. As show in Fig. 1, the optical telecommunication network is mainly consisting of three photonic parts all are made from glasses. First, transmitter contains laser source, nonlinear saturable absorber and all-optical switch to produce digital signal of light pulses for a certain acceptable intensity level. Second parts are fiber optic cable and amplifier, while the third part is photodetector. In the following sections a review of some of the most advanced photonic glasses and their used in optical telecommunication devices is given. Brief idea about each discussed technology is afforded to clarify the material requirements which are needed for that technology.

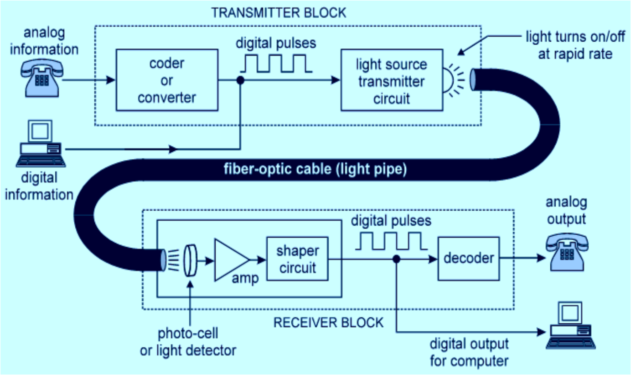

Figure 1. Schematic presentation for the different photonic parts of the very fast and ultrahigh capacity optical telecommunication network

2. Glass Optical Fibers

Optical fibers for telecommunication are made of silica. Doping with impurity oxides, such as GeO_2, TiO_2, Cs_2O, Al_2O_3, ZrO_2 and P_2O_5, rises the refractive index of pure silica in the core region. Doping with Boria B_2O_3 or Fluorine F lowers the refractive index of the cladding. Rare-earths such as $ErCl_3$ and Nd_2O_3 have been used to make fiber amplifiers and fiber lasers[9]. The central core is surrounded by a cladding layer, as shown in Fig. 2. Refractive index of the cladding is less than the refractive index of the core. The light rays travel through by reflection along the interface between the two transparent mediums. Total internal reflection causes the light to be guided down the fiber. Recently, specialty glasses and optical fibers are attracting much attention for their utility as the laser emitting and as well as amplifiers. An optical fiber glass is made from sodium–aluminum–borosilicate glass doped with PbSe quantum dots (QDs)[10]. A new germano-silica glass optical fiber doped with PbSe quantum dots for nonlinear optical

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applications such as saturable power limiter is developed [11].

There is a spectral region of 1150–1500 nm where in fact no efficient fiber lasers (or any other efficient lasers) exist. Bi-doped glasses are proposed as fiber lasers[12] because the glass can be applied to designing novel broadband fiber amplifiers working in C–L waveband, which is very promising for advanced optical communication systems. The recent progress in the development of lead silicate glass fibers with high nonlinearity tailored near-zero dispersion at telecommunication wavelengths, encompassing holey, all-solid microstructured and W-type fiber designs are discussed[13]. Tellurite glass is proposed as a host for broadband erbium-doped fiber amplifiers because of their excellent optical and chemical properties[14]. A new single mode Er^{3+}/Yb^{3+} codoped tellurite fiber with D-shape cladding geometry is fabricated. Phosphate glasses containing alkaline earth, alkali and mixed alkali oxides are proposed as cladding glasses for tellurite-glass core to realize highly nonlinear optical fibers with tailored chromatic dispersion[15]. Studies proposed low-loss fibers in the Ge–Se system. Ge–Se chalcogenide fibers are transparent in the near and middle infrared and show a high nonlinear refractive index. So, such fibers are of high interest for optical applications like all optical telecommunication provided that optical losses are sufficiently low[16]. Due to the thermal stability of GeO_2 glasses, incorporation of Ga_2O_3 into the ternary GeO_2–PbO–Na_2O system to provided a novel IR GeO_2-based optical fiber with high glass transition temperature[17].

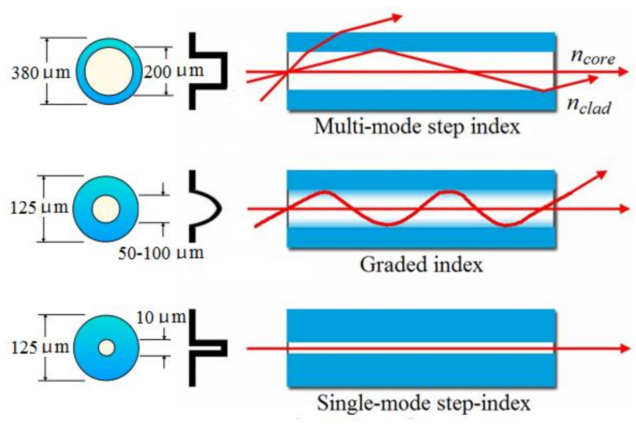


Figure 2. Optical fiber types and their constructions

Two sets of Er^{3+}-doped alkaline-free glass systems, MgF_2–BaF_2–$Ba(PO_3)_2$ $Al(PO_3)_3$ and $Bi(PO_3)_3$–$Ba(PO_3)_2$–BaF_2–MgF_2 are prepared to be used as active media. Comparison of the measured values to those of Er^{3+} transitions in other glass hosts suggests that these new glass systems are good candidates for broadband compact optical fiber and waveguide amplifier applications[18]. Ho-doped alumino–germano-silica glass fiber was prepared for laser emissions around 550 nm and 650 nm and near infra red emissions around 1050 nm and beyond 1726 nm[19]. Fiber nonlinear optical loop mirror is a valuable tool in signal processing applications[20].

A phosphate glass system was developed in order to incorporate high rare-earth ions concentrations[21]. The glass network was open with a linkage of the tetrahedrons very disordered and contains a larger number of non-bridging oxygens with the possibility to incorporate high doping concentration of rare-earth ions. This phosphate glass system was designed for ultra short single mode amplifiers with a high gain at 1.55 μm. Thulium-doped fiber amplifiers have been proposed as practical devices for the amplification of light signals in the S-band (1460–1530 nm) of the transparency window of standard telecommunications optical fiber[22]. Broadband near-infrared emission from Pr-doped borophosphate glass was prepared[23]. The emission band had three peaks centered at ∼1040, 1163, and 1470nm. So, Pr-doped glass can be used as an amplification medium for tunable lasers and broadband optical amplifiers for wavelength division multiplexing transmission system.

Germanium oxide (GeO_2) and tellurium oxide (TeO_2) based glasses doped by Pr^{3+}, Nd^{3+}, Er^{3+} and Tm^{3+} were produced to work as laser and amplifier devices for optical telecommunication wavelengths[24]. Er^{3+} doped Na_2O–Sb_2O_3–B_2O_3–SiO_2 glasses were developed for 1.5μm broadband fiber amplifiers[25]. Active waveguide lasers and amplifiers were fabricated by silver–sodium ion exchange in erbium–ytterbium doped phosphate glass substrates[26]. The basic elements of tapering chalcogenide optical fibers for the generation of extreme spectral broadening through supercontinuum generation were reviewed[27]. Advancements in glass clad semiconductor core optical fiber for its nonlinearity were also reviewed[28]. The third-order optical nonlinearity of the optical fiber is utilizing widely for the optical signal processing, white light generation and pulse reshaping. Thus design and fabrication of bismuth-silicate photonic crystal fiber was accomplished[29]. Chromium-doped, silica-based performs and optical fibers were prepared by modified chemical vapor deposition (MCVD) and have studied the influence of the chemical composition of the doped region on the Cr-oxidation states and the spectroscopic properties of the glass[30]. Glasses with composition $xNb_2O_5\cdot(30-x)MO\cdot70B_2O_3$[where M = Ca, Sr, Ba], which makes these glasses suitable for optical telecommunication devices, were prepared[31]. Glasses on BaO-$B_2O_3Al_2O_3$ and BaO-B_2O_3-Ga_2O_3 systems were grown by a new Floating-Zone Pulling Down method[32] to be used for photonic applications. The value of $\chi^{(3)}$ was two to three times larger than that of standard fused silica. Calcium lanthanum metaborate glasses of composition (wt%) 23.88CaO-28.33La_2O_3–47.79B_2O_3 was studied[33]. With an increase of TiO_2 content, the nonlinear optical properties are found to be on a par with several glasses reported for NLO applications. Copper nano composite glasses were prepared by the ion-exchange method[34]. The absorption spectra, fluorescence spectra and nonlinear optical transmission of the glass at 532 nm for nanosecond laser pulses were investigated. The optical and nonlinear optical properties of the glasses were found to be distinctly different below and above the glass softening temperature. Such flexibility in controlling the optical nonlinearity in these materials glasses them potential candidates for photonic applications.

Bi_2S_3 as an important semiconductor material with a direct band gap of 1.3 eV has widely been studied because of its excellent properties in photosensitivity. The third-order nonlinear optical properties were measured for sodium borosilicate glass doped with Bi_2S_3 in the form of nanocrystals ranging from 10 to 30 nm[35]. The band gap of the glass was reducing with increasing content of Nb_2O_5. The refractive index was found to increase with increasing Nb_2O_5 content, which makes the glass a suitable candidate for optical telecommunication devices. The n_2 measurements of Ge–Sb–S–Se system were made[36]. The nonlinear index increases up to 500 times the n_2 of fused silica with an increase in the Ge/Se ratio and decrease with an increase of the Ge/S ratio. Sulfide glasses were shown to have a nonlinear figure of merit (FOM) near or less than 1, at 1064 nm. The glasses could be good candidates for applications at telecommunication wavelengths (1.55 mm) or beyond. The physical characteristics and refractive index of several chalcogenide glasses based on the Ge_xSe_{100-x} ($15 \leq x \leq 25$) system were studied[37] for the purpose of the elaboration of single mode optical fibers.

3. Glasses for Fiber Lasers

In1963, Elias Snitzer added rare earths to the glass to build the first fiber glass laser[38]. The glass can absorb light and amplify it, emitting large amounts of power at a single wavelength. For optical telecommunications, the glass optical amplifiers could efficiently amplify light signals up to 10,000 times. Erbium was used in the form of trivalent ion Er^{3+} for being the laser-active dopant in silicate and phosphate glasses. In fiber laser (Fig. 3) the active gain medium is a single-mode optical fiber doped with rare-earth elements such as erbium, ytterbium, neodymium, praseodymium, and thulium[39, 40].

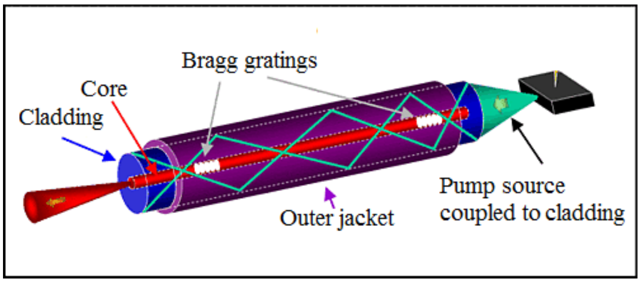


Figure 3. Schematic presentation of glass fiber laser construction used in telecommunication network

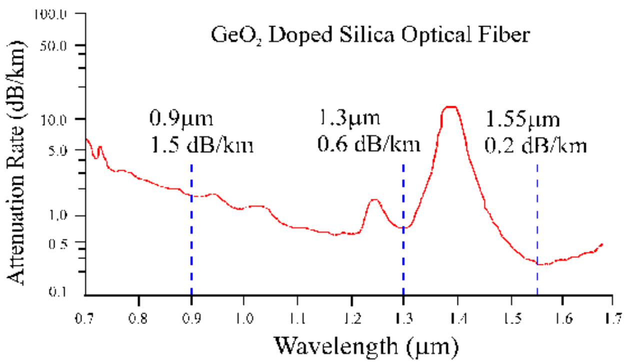
Fiber Bragg Gratings (FBG) is built in the fiber core to work as selective mirrors for the laser resonator. The gain medium forms the core of the fiber, which is surrounded by two layers of cladding. The lasing mode propagates in the core, while a multimode pump beam propagates in the inner cladding layer. The outer cladding keeps this pump light confined. Fiber nonlinearity provides gain for the fiber laser. Glass fiber lasers were made with over 1 kW of power which is enough to cut through an inch of steel. Also, Rare-earth ion doped TeO_2 and GeO_2 glasses were investigated as laser materials[24]. Heavy metal oxide and oxyfluoride glasses have considerable attention for their potential application in fiber lasers for the mid-infrared region, as well as for nonlinear optics. Among these glasses, tellurite glasses have been extensively investigated. A new fluorotellurite glass based on $(85\text{-}x)TeO_2\text{–}xZnF_2\text{–}12PbO\text{–}3Nb_2O_5$ (x = 0-40) system is prepared and studied for the fabricating mid-infrared optical fiber lasers[41].

An up-conversion emission was obtained in violet (408 nm) from Nd^{3+}-doped $93SiO_2{:}7TiO_2{:}20AlO_{1.5}$ glasses synthesized by the sol-gel process[42]. Although the up-conversion luminescence has a shorter lifetime and weaker intensity, it is of use to the development of sol-gel glass-based waveguide lasers operating at the violet wavelength. Er-doped SiO_2–TiO_2 binary glasses were investigated for fluorescence yields and decay times of the $^4S_{3/2}$ level of Er^{3+}[43]. The glass with TiO_2 showed enhanced up-conversion to be observed when compared to SiO_2 glasses doped with Al. The possibility of avoiding formation of Er-rich oxide clusters in $ErAl_3O_6$–TiO_2–SiO_2 glassy films was investigated[44]. Glasses containing 0.5, 1 and 3 mol% Er^{3+} were prepared using a precursor with a single, isolated Er-ion, $ErAl_3(OPr^i)_{12}$, in the metal–organic sol–gel route. The glasses exhibit luminescence both in the visible and IR under excitation of the 514.5 and 488 nm Ar^+ laser lines. Up-converted emission was also detected around 21000 and 24500 cm^{-1}. Tm^{3+}/Yb^{3+} co-doped tellurite glasses with the base compositions (in mol%) $80TeO_2\text{–}10K_2O\text{–}(9.9\text{-}x)TiO_2\text{–}0.1Tm_2O_3\text{-}xYb_2O_3$ (x=0.1, 0.3, 0.5, 1.5 and 2.0) was prepared [45]. The luminescence peaks of indirect sensitization upconversion excited by 800 nm laser diode were varied from 475 nm to 452 nm and to 468 nm with increasing Yb_2O_3. The corresponding luminescence intensity and the upconversion efficiency were also increased with Yb_2O_3 content.

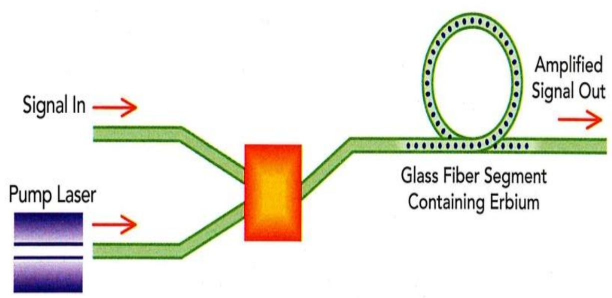
There is a considerable interest in compact pulsed high peak power laser sources emitting at wavelengths near 1.55 μm. Erbium- and ytterbium-doped YAG single crystals were obtained by the Czochralski method[46]. The effect of variation of erbium, ytterbium, chromium ions and glass base compositions on laser efficiency was described. Phosphate glasses with various Cr_2O_3, Yb_2O_3, and Er_2O_3 contents were prepared[47]. The effect of changing concentrations of Er^{3+} ions ($0.1\text{-}1.5 \times 10^{19}$ ions cm^{-3}) and sensitizers Cr^{3+} ion and Yb^{3+} ion ($2\text{-}16 \times 10^{18}$ ions cm^{-3} and $1.35\text{-}2.3 \times 10^{21}$ ions cm^{-3}, respectively) on laser performance were investigated. Lasers with repetition rates of 20 Hz at free-running and 15 Hz at Q-switched single mode were demonstrated by utilizing chemically strengthened laser glass rods. The glass compositions CeO_2-ZnO–Al_2O_3–PbO–B_2O_3[48] could be used to make laser material (with selective band gap). However, high power fiber lasers and their current status and future perspectives are discussed elsewhere[49].

4. Glasses for Fiber Amplifiers

In optical telecommunication systems, optical signals are inherent attenuated in the silica fiber at different wavelength, see Fig. 4(a). Erbium-Doped Fiber Amplifiers (EDFAs) are operating in the 1550 nm range, see Fig. 4(b). Since most telecommunication systems are still working at 1310 nm, considerable researches were done to find materials that would work in this range. Praseodymium-doped fluoride fiber amplifiers (PDFFAs) work at 1300 nm are using fibers made from zirconium fluoride or hafnium fluoride. The glass-forming region in the GeS_2–Ga_2S_3–PbI_2 system was determined[50]. The glass has a wide optical transmission window from 0.5 to 12.7 μm make these glasses the promising candidate materials for rare earth doped fiber amplifiers and nonlinear optical devices. Photoelectric materials such as chalcogenide glasses in the GeS_2–Sb_2S_3–CdS system[51] were used in the field of rare earth doped fiber amplifiers and nonlinear optical devices. Aluminum oxide waveguides were doped with erbium for applications in telecommunication to develop an integrated optical amplifier[52]. A series of ternary phosphate glass system require for IR photonic devices was synthesized[53] to be applied in C-band telecommunication systems around 1550 nm. The effect of replacing (divalent) ZnO with (monovalent) Na_2O on optical properties of the glass systems is investigated.



(a)



(b)

Figure 4. (a) the attenuation Ge-doped silica fiber at different wavelengths, (b) schematic presentation of glass optical fiber amplifier

5. All-optical Switching

The optical switch enables signals in optical fibers or integrated optical circuits to be selectively switched from one circuit to another or between different fiber transponders. Optical systems that perform this function by routing light beams are often referred to as "photonic" switches, independent of how the light itself is switched. An optical switch is the unit that actually switches light between fibers, whereas photonic switch is one that does this by exploiting nonlinear material properties to steer light (i.e., to switch wavelengths or signals within a given fiber). Fast optical switches, such as those using electro-optic or magneto-optic effects, may be used to perform logic operations. Included in this category are semiconductor optical amplifiers, which are optoelectronic devices that can be used as optical switches and be integrated with discrete or integrated microelectronic circuits. Fig. 5 illustrates a schematic presentation of optical switch; without switching pulse waves in leg 1 and 2 interfere destructively, so no output.

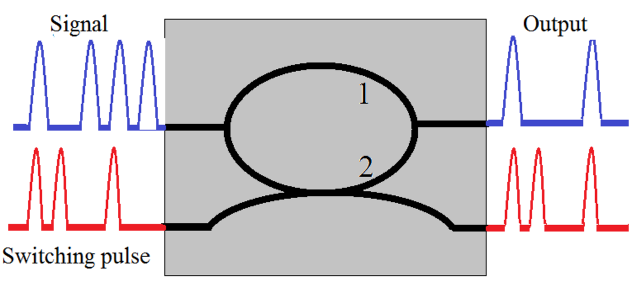


Figure 5. A schematic presentation of fiber optic interferometric nonlinear all-optical switch

With switching pulse; due to the nonlinear interaction the switching pulse causes a phase shift in the part of the signal pulse propagating in leg 2. As a result waves in 1 and 2 interfere constructively providing an output single. It has demonstrated that the nonlinear refractive indices of oxide glasses can be increased by the addition of heavy-metal-cations, such as Pb, Bi, and Ti[54-56]. The third-order susceptibility $\chi^{(3)}$ values were more than ten times larger than the $\chi^{(3)}$ from CS_2 and were more than 1000 times larger than the $\chi^{(3)}$ from conventional glass or silica fibers[57].

Ultrafast switching devices, using optical fibers and waveguide structures made of heavy element doped glasses, should use much less power than conventional silica fibers. Ultrafast third-order optical nonlinearity of Ge–Ga–Ag–S chalcogenide glasses at the wavelength of 820 nm has been measured[58]. These chalcogenide glasses would be expected as promising materials applied on all-optical switching devices. Also, ultrafast third-order nonlinear optical responses of $GeSe_2$–In_2Se_3–CsI chalcohalide glasses have been measured at 1064 nm. The glass was a promising material for all-optical switching devices[59]. Two series of metal iodide doped chalcohalide glasses GeS_2-Ga_2S_3-$x$$PbI_2$ were prepared and characterized for third-order nonlinearity [60]. Glass formation and third-order optical nonlinear characteristics of bismuthate glasses Bi_2O_3-GeO_2-TiO_2 system was prepared for applications of all-optical switching or related optical devices[61]. Nonlinearity in bent optical fiber was studied to use bent glass fiber as an optical switch[62, 63].

Optical glasses with large non-resonant nonlinear refractive index are good materials for all-optical switching devices and mode-locked solid-state lasers. Glasses have advantages compared to semiconductors, semiconductor - doped glasses, and organic materials because of their fast response times, negligible linear loss, and small two-photon absorption (TPA) in the wavelength range of interest. The studies of sulfide glasses reported particularly large nonresonant optical nonlinearities. Selenides have been identified as candidate materials for nonlinear optical applications. Because of its large atomic radius compared to oxygen in oxide glasses and sulfur in sulfide glasses, selenium was believed to be the key to the nonlinear optical properties in selenide glasses. Therefore, a complete study of nonlinear optical properties of sulfo-selenide glasses for all-optical switching at telecommunication wavelengths (1330 nm and 1550 nm) was carried out[64]. The third-order optical nonlinearities of Ge–Ga–Sb(In)–S chalcogenide glasses have a wide transparency in the visible region, high nonlinear refractive index n_2 and low nonlinear absorption coefficient β [65].

PbO-B_2O_3 glasses were prepared to be used in ultra-fast all-optical switches[66]. The nonlinear index of refraction n_2 was on an order larger than a CS_2 solution (n_2 0.98 $\times10^{-11}$esu). The composite materials with silver or copper metal particle exhibit larger nonlinear refractive index than the related lead glasses with saturation absorption property at 532 nm from 1.02 to 7.09$\times10^{-2}$ GW/cm^2. LBG glass was prepared by melting mixtures of Pb_3O_4, Bi_2O_3 and Ga_2O_3 at 900 ℃ in a gold crucible[67] where the nonlinear response in the LBG glass is mainly derived from an electronic origin and suggests a potential application for a femtosecond Kerr shutter for all optical switching.

Application of chalcogenide As_2S_3-based glass fibers in ultrafast all-optical switches was established[68] since the nonlinear refractive index was higher by two orders of magnitude than that of silica glass fiber and the nonlinear absorption due to two-photon absorption was negligible. Switching time of 12 ps and a switching power of 5 W could be achieved using a 10-ps gate pulse and only a 1 m chalcogenide glass fiber. The ultrafast nonlinear optical properties of Bi_2O_3–B_2O_3–SiO_2 oxide glass were studied at wavelength of 800 nm[69]. The nonlinear response time of this Bi-doped glass was measured to be <90 fs. The nonlinear refractive-index n_2 was estimated to be 1.6$\times10^{-14}$ cm^2/W. Due to semiconductor-like behavior of zinc oxide, a B_2O_3–Li_2O–WO_3 glass was doped by ZnO to adapt its optical nonlinearity for photonics applications[70, 71]. The glass exhibits low two-photon absorption which is ideal for all-optical signal processing devices. The Figure of Merit needed for optical switching applications was estimated as shown in Fig. 6. The study reveals the importance of determining the dispersion of the optical nonlinear parameters to find out the appropriate operating wavelength that provides optimum Figure of Merit (FOM) of the glass.

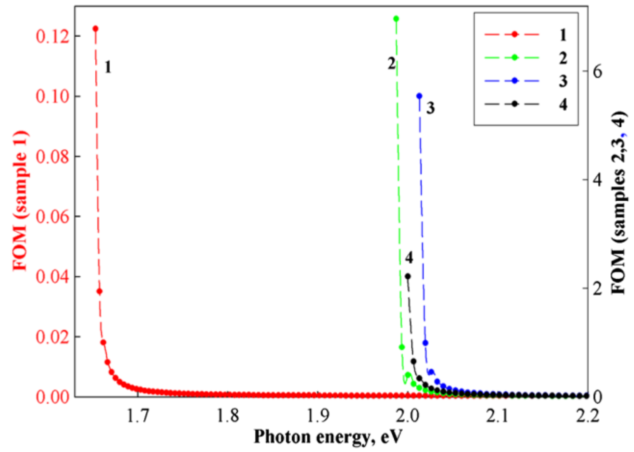


Figure 6. Graphical relation of figure of merit against photon energy

6. Optical Power Limiter

Optical-power limiters (OPLs)-such as saturable absorbers-were designed to allow normal transmission of light at low intensities and limited transmission at higher irradiance, so they can be used for producing ultra-short laser pulses, see Fig. 7. Power limiter devices were widely used for optical communications. Glasses should exhibit fast response times, absorb over a broad wavelength range and exhibit low optical loss. The equation describes the work of power limiter is: $\alpha(I) = \alpha_0 + \beta I$. Here α_0 is the linear absorption coefficient and β is the nonlinear absorption coefficient.

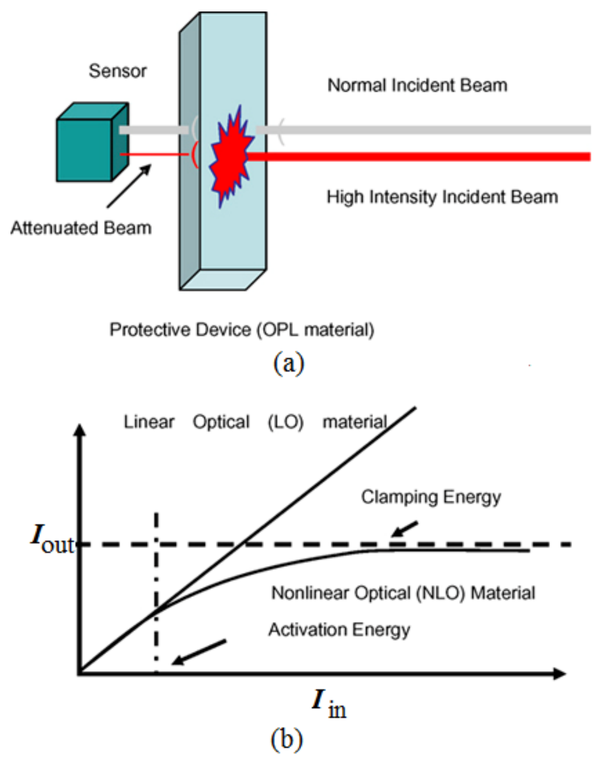


Figure 7. (a) schematic presentation to nonlinear power limiter and (b) input output energy level relation

Gold metallic nanoparticles were fabricated in lanthanum borate glass matrix[72]. The nonlinear optical transmission properties of these glasses showed that they were very good saturable absorbers (SA) at medium input intensities. As-prepared glass sample showed reversible saturable absorption (RSA) behavior at higher light intensities, indicating their potential use in optical limiting devices. Sulfide–halide glasses (GeS_2–Sb_2S_3–CsI) with high nonlinear refractive index and low nonlinear absorption were prepared[73]. Metal nanocluster composite glass was formed by Cu ion implantation into silica using metal vapor vacuum arc ion source providing high nonlinearity[74]. Nonlinear saturable absorption of the sodium borosilicate glass containing nano crystallites Bi_2S_3 was prepared[75]. The transformation from saturable absorption to reverse saturable absorption in the glass was observed with the increase of the input light intensity of the laser used. The mechanism of the third-order nonlinear optical absorption and reverse saturable absorption in nano colloidal $Ge_{28}Sb_{12}Se_{60}$ chalcogenide glass were also observed[76]. The figure of merit was defined for chromium-doped aluminate and silicate glasses[77] to compare the performance of different materials as saturable absorbers. The preparing conditions that lead to a glass saturable absorber with better figure of merit have been investigated. A Q-switched Cr:LiSAF laser was used for the saturable absorption measurements.

Recent developments of saturable absorbers that were based on semiconductor quantum-dot (QD) structures for the passive mode locking of near-infrared lasers were outlined[78]. The performance of solid-state (Yb^{3+}, Nd^{3+} and Cr^{4+}-based), Yb-doped fiber and integrated semiconductor lasers has been described within the context of ultrashort-pulse generation using these types of QD-based modulators. Attention was paid to the nonlinear parameters of the QD-based saturable absorbers that determine the quality of the mode locking in such laser systems.

7. Photosensitive Glass and Fiber Bragg Gratings

Photosensitivity is refractive index and/or absorption changes that can be induced by radiation (light, laser irradiation, g, X-ray, etc) in a glassy material. Photosensitive glass was explored in the 1950s for micro-structuring using ultraviolet (UV) light. Photochromic materials changes in color (absorption) when exposed to light due to activation of a dopant. Photosensitivity was used for the fabrication and design of optical devices such as fiber Bragg gratings (FBG)[79-84]. FBG grating was generated by exposing the core (5 μm) of an optical fiber to a fringe pattern of ultraviolet light at 240 nm to breakdown the chemical bonds of GeO and hence lowering the core index of refraction, see Fig. 8[85]. The ultraviolet light induces local changes in the refractive index of the core. A change in refractive index is seen as a tiny mirror by the light trying to pass through the grating, and a small portion will be reflected as shown in Fig. 9[86].

By changing (tuning) the distance and amplitude between the grating periods the wavelengths and amount of reflected light can also be tuned as shown in Fig. 10[87]. With non-uniform period, the result is a chirped FBG. This type of grating can be used to spectrally narrowing the light pulse which in turn increases the capacity of propagated information. Therefore, photosensitive germanium-doped multicomponent silicate glasses with different amount of boron oxide and sodium oxide were prepared[88]. Understanding the role of sodium and boron is important in order to increase the photosensitivity of germano-silicate glasses, for their interest in the field of ion-exchangeable glasses for photonic waveguides and Bragg-grating based devices.

Over the last two decades UV-induced change (Δn) index profiling in SiO_2 glasses was widely used for production of in-fiber Bragg grating-based (BG) optical devices for photonics industry. A review on UV laser processing and multiphoton absorption processes in optical telecommunication fibers materials was afforded[89]. The potential of photorefractive materials including photosensitive glasses in photonic devices such as information storage, processing, and optical fiber communication systems were reviewed[90].

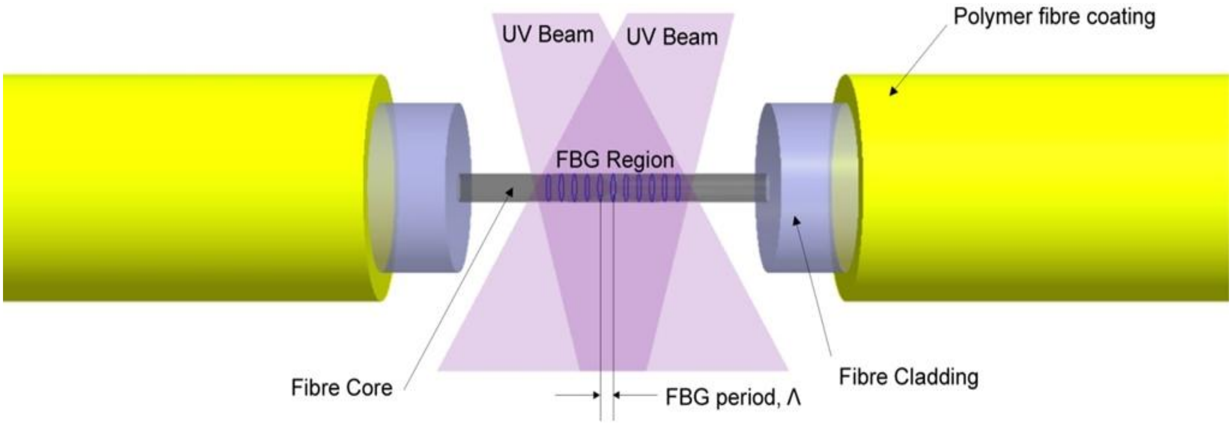


Figure 8. Interferometric method to produce FBG

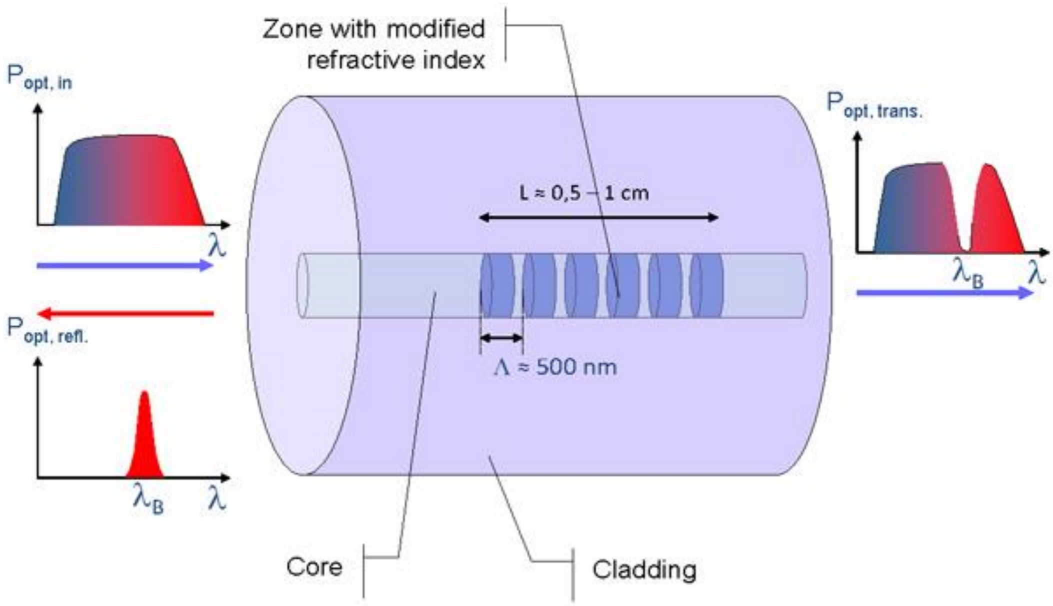


Figure 9. Schematic presentation of the transmitted and reflected pulse signals through FBG

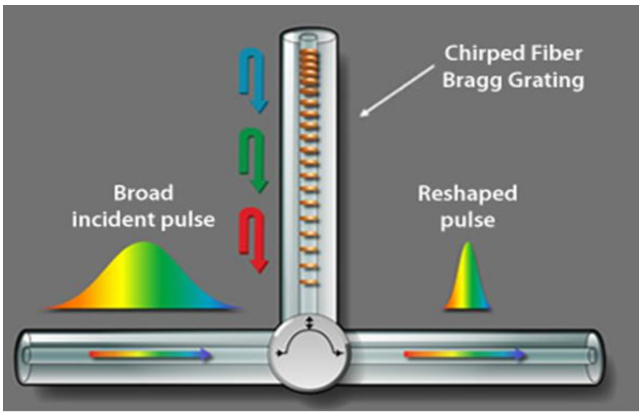


Figure 10. Schematic presentation for the way of work of a chirped FBG

8. Magneto-optic Glass and Fiber Insulator

Fiber laser devices used in telecommunication require protection from back-reflected beams. Therefore, magneto-optic materials can be used to make optical fiber isolators (Faraday rotator) and to generate optical switch as well based on the Faraday effect[91-94]. Rotation of the plane of polarization of light occurs when it passes through a transparent material in an external magnetic field, as shown in Fig. 11.

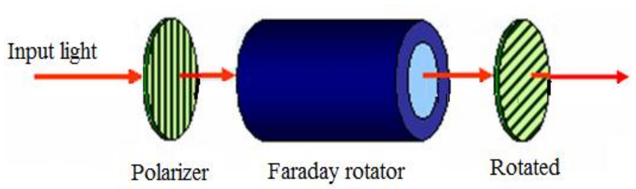


Figure 11. Construction of Faraday optical fiber rotator

Magneto-optic effect depends on electric and magnetic dipole moments of atoms and ions of the glass components and on magnetic field intensity, not on the light intensity. Diamagnetic ions with full-filled shells have zero orbital moment or zero permanent magnet moment. Whereas paramagnetic ions such as rare earth and transition metals exhibit permanent magnetic moment due to their unfilled inner electronic shells.

In the absence of an applied magnetic field, the average magnetic moment is zero. Applying a magnetic field causes a limited current around the nucleus which produces a magnetic moment that is opposite to the applied field. Accordingly, the magnetization M (results from the orientation of the permanent magnetic moment for paramagnetic ions) is dependent on magnetic field H and the microscopic diamagnetic susceptibility χ where: $M = \chi H$. The microscopic diamagnetic susceptibility depends on paramagnetic atom density, permanent magnetic moment, number of electrons per atom and the charge distribution in the atoms. Optical dispersion and high refractive index glasses which containing cations with easily polarized outer electronic shells such as Te^{4+}, Bi^{3+}, Pb^{2+} or anions such as S^{2-}, Se^{2-} show large diatomic susceptibility. The orbit of the 4*f* electrons in rare earths is shielded by the 5*s* and 5*p* outer shells thus they kept the same as in the free atom. Ions such as Ce^{3+}, Pr^{3+}, Tb^{3+} and Dy^{3+} acquire large magnetic susceptibility.

Magnetic garnet materials produce very large specific rotation and have been used usually in the fabrication of isolators in optical fiber networks. The move towards integration of active and passive optoelectronic devices to make photonic ‘‘chips’’ is now motivating research. Oxide glasses with nonlinear refractive index, n_2, were commonly investigated for future photonic applications such as ultra-fast switching and electro-optic modulators[95].

Deposit pattern crystalline magnetic garnet films onto semiconductor substrates suffer from lattice mismatch or growth-induced magnetic anisotropy (modal birefringence). High modal birefringence is a problem because it produces oscillation of the principal axis of polarization, rather than a linear increase of the rotation angle of linearly polarized light with distance. Therefore, there is a growing interest in amorphous chalcogenide glasses (As–S based glasses) to be used in integrated optics. Also, because their high non-linear refractive indices at infrared wavelengths it suggests that they can be used to make chips capable of all-optical processing. Due to their high linear refractive indices and dispersion in the infra-red indicates high Verdet constant, *V*. As–S based glasses were studied at several wavelengths interest for integrated optics applications. Measurements of magneto-optical rotation in gallium lanthanum sulphur ($Ga_{28}La_{12}S_{42}O_{18}$) glasses were performed at 543 nm. Verdet constant was found to be as high as 0.2 min/G.cm.

Verdet constant is linearly proportional to the optical dispersion $dn/d\lambda$ through the expression $V = \frac{e}{2mc^2}\lambda\frac{dn}{d\lambda}$. Verdet constant is considered to be of two types depending upon the ion or ions that are incorporated in glass: diamagnetic or paramagnetic. Most normal network former and modifier ions in glass would give rise to diamagnetic rotation. Diamagnetic glasses generally have small and positive Verdet constants, which are almost independent of temperature. Whereas paramagnetic glasses usually have large and negative Verdet constants, which are generally inversely proportional to temperature. The rare-earth and transition ions are examples of paramagnetic ions. Faraday Effect in TiO_2-SiO_2 glasses and the Verdet constant of silica glasses for wavelengths of 632.8 and 785 nm were evaluated [96] and was found to be $(3.930 \pm 0.017) \times 10^{-6}$ and $(3.237 \pm 0.068) \times 10^{-6}$ (rad/A), respectively. Table 1 lists the Verdet constant of several commercial magneto-optic glasses at room temperature[97].

Table 1. Verdet constant of several commercial magneto-optic glasses at room temperature

Type	Glass	V/rad T^{-1} m^{-1}
FR-5(Hoya)	Tb^{3+} doped borate	-71
$Pr(PO_3)_3$	Meta-phosphate	-39.6
FR-4(Hoya)	Ce^{3+} doped borate	-30
SF-59(Schott)	High PbO contained silicate	28.5
SiO_2	Fused silica	4.0

9. Acousto-optic Glasses for Optical Deflector and Modulator

Acousto-optic effect provides optical signal manipulation in the far IR (6-12 μm) without using high voltages. The effect is set up when an ultrasonic wave passes through glass causing variations on its refractive index to give temporarily effective diffraction gratings within the glass providing a fast deflection or modulation for transmitted light. A laser beam traveling in a plane perpendicular to the direction of travel of this acoustic wave will be deviated from its original path by an angle depending on the frequency of the acoustic grating. The grating efficiency to diffract light depends on material's parameters and on the acoustic power launched into the glass. A value of 1500 relative to silica is generally considered high enough for most applications.

Acousto-optic glasses which have a high transmission at 1.55 μm would give potential application to switching systems within silica fiber networks, whereas transmission at 2.06 μm is suitable for Ho-YAG laser systems. Moreover, glasses working at 10.6 μm would have application in mid IR frequency modulation. The acousto-optic glasses are used as modulator or deflector in optoelectronic and photonic devices. The figure of merit M_{OA} of the diffraction efficiency of acousto-optic materials is given by $M_{OA} = \frac{n^6 p^2}{\rho v^3}$ where ρ is the glass density, *n* is the refractive index, *v* is the acoustic velocity and *p* is the photo-elastic constant. In addition to have low losses at the acoustic and optical wavelengths, acousto-optic glasses should also have a large refractive index, photo-elastic constant and small sound velocity. Tellurite glasses with photo-elastic constant (Pockles coefficient) $p = 0.09$ have $M_{AO} = 3.9$ whereas the sulfide glasses have $M_{AO} = 19.0$ for $p = 0.18$. A short review of chalcogenide glasses in acousto-optic devises was reported herein[98].

Selenide and telluride glasses were usually chosen over the sulphides due to their large refractive indices and extended IR edges. System such as As-Se-Te is considered better than Ge-Se-Te glass system due to its weak phase separation since $AsTe_{3/2}$ structure units are more stable the $GeTe_{4/2}$ structure units[99]. The fundamental absorptions of As-Se and As-Te bonds are at longer wavelengths (46.1 and 63.3 μm, respectively) compared with Ge-Se and Ge-Te bonds (42.7 and 51.0 μm, respectively) providing glasses with wide transmission ranges. A small amount of Ge may be used due to its stability enhancement and reduction of acoustic loss. Since lead is heavy element it may also be used up to 10 at.% to give large increase in refractive index in system such as As-Se-Ge before devitrification[100].

Acousto-optic investigations of glass alloys of different compositions were done in wide ranges of optical wavelengths, temperatures (77–400 K) and frequencies (10–1800 MHz)[101]. The study of photo-elastic properties of narrowband semiconductors such as InSb mono-crystals founded an anomalous strong acousto-electron interaction due to deformation potential of electron part of photo-elastic tensor component. Study of sound attenuation in multicomponent phosphate glasses revealed a double-well potential nature of the glass structure. Study of resonance photo-elastic effects in layered GaSe crystals has shown a large anisotropy of photo-elastic constants due to the anisotropy of bonding forces leading to exiton two-dimensional wave function in GaSe crystals. Study of nonlinear elastic properties showed a high anisotropy of anharmonicity of bonding forces which causing a mechanical anisotropy in $KY(MoO_4)_2$ layered crystals.

A nonlinear propagation of a surface acoustic wave in thin lead films was studied. Considerable suppression of higher harmonic generation arising from significant concentration of the wave energy in the metal film area was observed. Ultrasound effect on spectral parameters of laser hetero-structures has resulted in realization of laser frequency modulation. Binary glass Si–Te system such as $Si_{20}Te_{80}$ alloy has high value of the acousto-optic efficiency which provides an acousto-optic modulator for wide IR region. On other hand, ternary telluride glass systems such as $Ge_{19}Te_{72}Se_9$ alloy have high optical homogeneity and transparency window at $\lambda \sim$ 10-11 μm (CO_2 laser, λ = 10.6 μm). Also because of its lower acoustic attenuation, the $Ge_{19}Te_{72}Se_9$ glassy alloy is well competitive with the $Si_{20}Te_{80}$ glassy alloy in fabrication of modulators for the mid-IR spectral range.

The M_{AO} in $Si_{20}Te_{80}$ glass modulator designed for 1.7-10.6 μm IR region was ~7 times and ~5 times of those of mono-crystalline Ge,Ga_2Se_3 glass and amorphous Se values[102]. $Si_{20}Te_{80}$ based acousto-optic cell was used for amplitude modulation and deflection of IR light beam optically focused; λ = 10.6 μm (CO_2 gas laser), 3.39 μm (He-Ne gas laser), 3.3 μm (based on InGaAsSb/InAsSbP double heterostructure) and 1.87 μm (GaInAsSb diode lasers) and that is coming from the end of an As_2S_3 fiber λ = 3.3 μm. Modulation efficiency up to 90% at acoustic power ~0.5W and response $\tau < 0.3$ μs was obtained. The modulator may be used for diode laser spectroscopy to make mode selection or wavelength selection within lasing pulse. As–Ge/Pb–Se/Te glasses were investigated for their suitability to be used in acousto-optic devices. A figure of merit of As–Se–Ge–Te_{20}–Pb_5 glasses was reported at 10.6 μm, relative to the M_{OA} value of SiO_2 at 632.8 nm[103].

The energy level manifolds of trivalent praseodymium-doped materials allow several transitions in the visible region. Fiber laser actions have been reported in several Pr^{3+}-doped materials and fluorzirconate. With the fluorzirconate fiber, continuous wave laser action at 491 nm, 520 nm, 605 nm, 635 nm and 715 nm were reported under direct pumping with an Argon ion laser[104]. However, due to poor performance of Argon ion laser for the pumping wavelength of 476.5 nm, pulse laser operation of a 4cm long Pr^{3+}-doped fluoride-glass fiber laser pumped by InGaN laser diodes (444nm) using an acousto-optic modulator was demonstrated[105]. Maximum laser peak power of 105.6 W (2.1 μJ/pulse) with a pulse width of 20 ns at an 8.3 kHz repetition rate for a 607 nm wavelength was obtained. Wavelength tunable Q-switch pulse laser oscillation in the visible region (488–491, 520–526, 601–624, 631–644nm) has been obtained.

Fiber optic acoustic sensor-based detection for the acoustic signals propagating and partial discharges inside high voltage power transformers with high resolution and high frequency was developed[106]. The fiber optic sensor used a silica diaphragm and a single mode optical fiber encapsulated in a silica glass tube to form an extrinsic Fabry–Perot interferometer.

Nd^{3+}-doped potassium barium aluminium phosphate glasses K_2O-BaO-Al_2O_3-P_2O_5 were prepared with Nd concentration of 4% to be used as acousto-optic modulator [107]. The acousto-optic figure of merit of the glass was comparable to that of quartz. A monolithic laser fabricated from Nd-doped phosphate glass was described in which unidirectional and hence single-frequency operation is enforced by the acousto-optic effect in the laser medium [108]. Reliable single-frequency output could be maintained with an applied radio-frequency power of 0.2 W. Output powers up to 30 mW for 400 mW of pump power have been achieved.

10. Conclusions

After revision of some of recent photonic technologies, glasses have proven their eligibility and competitiveness with respect to other optical materials. Particularly, photonic glasses are considered as essential materials for optical telecommunication devices. Furthermore, recent results on oxide glasses confirmed their competence as materials for photonics. There are two possible means for the future research to achieve highly competitive photonic glasses; first, continuously developing of new glass compositions, with lower glass transition temperatures. Second, developing oxide glasses containing high prolarizable ions implanted in ingenious host glass compositions. It allows obtaining a high FOM within the operating wavelengths used for information technology and optoelectronic devices. The synergetic effect of simultaneous applying of both means could offer a good future for glass photonic applications.

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