External Electromagnetic Field Induced Electronic Structures and Novel Optical Functions of Rare-Earth-Ion-Doped Glasses

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We researched the realization of novel optical functions of glass by combining an external electromagnetic field induced electronic structure and rare-earth-ions. We reviewed the phenomena, mechanisms, and the applications of photostimulated luminescence induced by X-ray, long-lasting phosphorescence by ultra-violet light, space-selective manipulation of the valence state of rare-earth-ion, and the formation of rare-earth-ion-doped optical waveguide for light amplification by a focused infrared femtosecond laser. The proposed concept will lead to a new possibility in the realization of novel optical functions for rare-earth-ion-doped glasses.

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1. Introduction

Glass was first produced more than 5000 years ago. Now, glass is widely used in our daily life. We can even say that there could be no highly civilized society without glass. Why is glass so widely used? Because glass is homogeneous, transparent and can be easily fabricated to various forms such as a bottle, a flat plate of large size or a fiber. Moreover, almost all elements such as rare-earth, transition metals and noble metals in the periodic table can be "stuffed" into glass. This results in glass that is splendidly colorful with various functions.

However, glass has its own weak points due to its random network structure and defects introduced during the fabrication processes. For example, glass is brittle and heavy, therefore the market for glass bottles has been eroded by metal, plastic, and paper containers. In addition, due to its random structure, the intensity of luminescence of glass is weaker than that of crystal with similar composition. In the coming information technology era, however, we can expect novel optical elements with functions of ultrafast switching, ultrahigh memory and optical amplification fabricated by glass. Therefore, it is necessary to research the development of glass with novel optical functions.

2. Basic research concept: the realization of novel optical functions by combining an induced electronic structure and rare-earth-ions

In 1994, Hirao proposed a basic research concept of "induced structure": He especially paid attention to the fact that glass is metastable from the viewpoint of thermodynamics. A metastable state of glass is easily changed to other states in an external electromagnetic field. Novel optical functions can be generated by controlling the external electromagnetic field induced electronic structure. A similar concept called "defect engineering" was proposed by Hosono. The light-induced fiber grating by Hill et al. and the observation of second harmonic generation in optical fiber by Osterberg and Margulis are among the excellent pioneering applications of induced structures.

Rare-earth has been used widely in various fields such as phosphors, magnetic materials and superconductors. The function of rare-earth-ion in materials science is divided into two parts. One originates from the electron configuration of 4f orbital of rare-earth, and the other from the state of chemical bonding of rare-earth e.g. the radius of ion, and the length of chemical bond. Several important properties of rare-earth-containing materials originate from the special 4f electronic structure of rare-earth. As has been pointed out in the introduction, a large amount of rare-earth can be stuffed into glass. Glass is an excellent matrix for rare-earth-ions to realize various functions. So far, the optical properties of glasses doped with rare-earth-ions have been investigated intensively, and these glasses have been used as materials for lasers, optical amplifiers and so on. However, only a few studies have been performed on the external electromagnetic field induced structure and property of rare-earth-ion-doped glasses.

Figure 1 shows the realization of novel optical functions by combining an external electromagnetic field induced structure and rare-earth-ion. If we can control the external electromagnetic field induced structure and the concentration, variety and valence state of rare-earth-ion in glass, in particular, if we can space-selectively control the induced...
structure or induce 3-dimensionally and periodically distributed electronic structure in glass, we expect that the novel optical functions of rare-earth-ion-doped glass will be achieved. From the viewpoint of practical applications, we expect to obtain a glass with properties superior to corresponding single crystals.

In this article, we review the phenomena, mechanisms and the applications of photostimulated luminescence induced by X-ray, long-lasting phosphorescence induced by ultra-violet light and infrared femtosecond laser, space-selective manipulation of the valence state of rare-earth-ions, and the formation of rare-earth-ion-doped optical waveguide for light amplification using a focused infrared femtosecond laser.

3. X-ray induced photostimulated luminescence in rare-earth-doped glasses

Photostimulated luminescence, a phenomenon due to the photostimulated recombination of holes and electrons at traps which leave electrons in a long-lived excited state, has attracted considerable attention in recent years. In photostimulated luminescence, a material excited by a light for example, after the irradiation by X-rays, emits a light 2 whose wavelength is usually shorter than that of excitation light 1, and the intensity of light 2 is proportional to the irradiation quantity of the X-ray in a certain dynamic range.

Photostimulable phosphor, BaFBr: Eu\(^{2+}\) (X=Br, I), is now widely used as a detector in X-ray radiography. An imaging plate made of BaFBr: Eu\(^{2+}\) (X=Br, I) has excellent characteristics, such as a wide dynamic range extending over more than five orders of magnitude, and high sensitivity which is one hundred or one thousand times more sensitive than silver chloride films which are still used as X-ray image receptors.

If photostimulable luminescence phosphor could be made of glass, that would be important from the viewpoint of practical application. We have observed the photostimulated luminescence phenomenon in reduced rare-earth-ion-doped glasses. We assume mechanism for the photostimulated luminescence in the glass is similar to that of the well studied BaFBr: Eu\(^{2+}\) photostimulable phosphor. Eu\(^{2+}\)-doped fluoroaluminate glass was fabricated in a reducing atmosphere. Figure 2 shows the decay curve of the photostimulated luminescence at 400 nm of the X-ray irradiated sample, when excited continuously by the He-Ne laser (633 nm). The emission at 400 nm can be assigned to the 5d-4f transitions of Eu\(^{2+}\) ions. The emission decayed when the He-Ne laser continuously irradiated the sample.

Since we observed no emission at 400 nm in the unirradiated sample, the emission at 400 nm is not due to upconversion or to a multi-photon absorption process. It is a phenomenon typical of photostimulated luminescence as observed in the BaFBr:Eu\(^{2+}\) phosphor. The mechanisms of photostimulated luminescence have been investigated intensively. Even for the BaFBr: Eu\(^{2+}\), however, the exact mechanism is still not clear. There are at least three models, which describe the photostimulated luminescence process in BaFBr: Eu\(^{2+}\). Takahashi et al. made experiments to confirm the mechanism of photostimulated luminescence in BaFBr: Eu\(^{2+}\). The proposed mechanism is that Eu\(^{2+}\) ions are ionized by X-ray irradiation and converted to Eu\(^{3+}\) ions either directly or by trapping holes, and electrons excited to the conduction band are caught by F\(^{−}\) centers (halogen ion vacancies) to form F centers. Then the irradiation of light in green to red stimulates luminescence, trapped electrons are liberated to the conduction band and return to Eu\(^{3+}\) ions converting them to excited Eu\(^{2+}\) ions, and thus the Eu\(^{2−}\) luminescence is produced. Moreover, a study by Hangleiter et al. has shown that no Eu\(^{3+}\) is formed upon X-ray irradiation. Moreover, the model proposed by Takahashi et al. does not specify how charge compensation is achieved when negative ion vacancies (F\(^{−}\) centers) are present during crystal growth. On the other hand, Seggern et al. attributed the photostimulated luminescence to a recombination of an F center and a hole center in close proximity, where charge transfer after photostimulated luminescence occurs through tunneling and not through the conduction band. More recently a new model of photostimulated luminescence was proposed by Harrison et al., in which photoexcited luminescence occurs when trapped electrons and holes migrate together to form loose clusters around Eu\(^{2+}\) and recombine after photostimulation.

All models propose that electrons and holes are formed in BaFBr: Eu\(^{2+}\) after X-ray irradiation. Some of the electrons are caught by F\(^{−}\) centers to form F centers, while some of the holes are caught by the hole-trapping center. Then, by the excitation of the He-Ne laser, trapped electrons are liberated and recombined with the trapped holes, resulting in the characteristic luminescence of Eu\(^{2+}\). Figure 3 shows the X-ray absorption spectra of Eu\(^{2+}\)-doped fluoroaluminate glasses, upon X-ray irradiation. Compared with Eu\(^{2+}\) and Eu\(^{3+}\) containing crystals, it is clear that a part of Eu\(^{2+}\) converts to Eu\(^{3+}\) upon X-ray irradiation, and the concentration of Eu\(^{3+}\) increases with increases in the X-ray irradiation duration. Eu\(^{2+}\) ions are ionized by X-ray irradiation and converted to Eu\(^{3+}\) either directly or by trap-
We observed a broad absorption band peaking at 500 nm ranging from 400 to 700 nm in the photostimulated excitation spectrum of X-ray irradiated BaFBr: Eu\(^{2+}\), which we attributed to the absorption of F\((P^-)\) center.\(^{21}\) Electron and hole traps were also observed in \(\gamma\)-ray irradiated RF\(_3\) (R=alkaline earth ion)–AlF\(_3\) containing fluoride glasses. The photostimulated excitation spectrum of the X-ray irradiated sample had three broad bands at 540, 630, and 680 nm. Such bands are due to electron traps, i.e., quasi-F-center centers, which may have deformed structure compared with F-centers in crystals. Therefore, we assume that quasi-F-center centers and Eu\(^{2+}\) ions or other defects act as electron and hole traps in the photostimulated luminescence, respectively.

We also observed photostimulated luminescence in various rare-earth-ion-doped glasses.\(^{9)-11}\) When the Ce\(^{3+}\)-doped borate glass samples were excited by the He–Ne laser (633 nm) after the X-ray irradiation, we observed an emission at about 360 nm, which decayed with the constant excitation by the He–Ne laser. The intensity of photostimulated luminescence increased exponentially with increases in the molecular weight of glasses. Moreover, the peak of the photostimulated luminescence excitation shifted to the longer wavelength in the order of Li, Na and K.

Therefore, it should be possible to control the wavelength of photostimulated luminescence, X-ray sensitivity and most appropriate wavelength of second excitation light by selecting species of rare-earth-ion and glass compositions. Photostimulable luminescence glass is expected to be a new material for 2-dimensional X-ray sensor.

UV light and focused femtosecond laser induced long-lasting phosphorescence in rare-earth-ion-doped glasses

The long-lasting phosphorescence is a phenomenon due to the thermostimulated recombination of holes and electrons at traps that leave electrons or holes in a metastable state at room temperature.\(^{27}\) The activating energy of the trapped electron or hole released from a trapping center in long-lasting phosphorescence is far lower than that in the case of photostimulated luminescence, thus an electron or hole can be released from the trapping center by thermal energy at room temperature. We observed long-lasting phosphorescence phenomenon in various rare-earth-ion-doped glasses.\(^{12)-14}\) Figure 4 shows the decay curves of the phosphorescence at 510 nm from the 40SrO·(60-\(x\))Al\(_2\)O\(_3\)·(60-\(x\))-SiO\(_2\)·0.05Eu\(_2\)O\(_2\)·0.05Dy\(_2\)O\(_3\) (xED) glass samples after irradiation by UV light for 30 s. The intensity of the phosphorescence increased with an increase in Al\(_2\)O\(_3\) concentration. The decay curve of the 30ED and 30E samples overlapped each other.

Usually, incorporation of rare-earth ions such as Eu\(^{2+}\), Sm\(^{3+}\), Dy\(^{3+}\) into phosphors largely changes the phosphorescence properties of the phosphors; therefore, such rare-earth ions are proposed to act as electron or hole trapping centers.\(^{28}\) The mechanism of the long-lasting phosphorescence in Eu\(^{2+}\)–Dy\(^{3+}\) doped strontium aluminate phosphor has been investigated by Matsuzawa et al.\(^{29}\) Based on photoconductivity measurements, they proposed that under UV-blue light irradiation, Eu\(^{2+}\) is excited by the \(4f^6 \rightarrow 4f^5 5d\) transition, and then the hole is thermally released from Eu\(^{2+}\) into the valence band and trapped by a Dy\(^{3+}\) ion. Thus, Eu\(^{2+}\) and Dy\(^{3+}\) are converted into Eu\(^{+}\) and Dy\(^{4+}\), respectively. Introduction of Dy\(^{3+}\) into the Eu\(^{2+}\) doped strontium aluminate results in the creation of a highly dense trapping level, which locates at a suitable depth so that the trapped hole is thermally released at a proper rate at room temperature. After the termination of the exciting light, the hole ther-mally released from Dy\(^{4+}\) returns to the excited Eu\(^{+}\), and the phosphorescence due to the \(4f^6 5d \rightarrow 4f^7\) transition of Eu\(^{2+}\) is emitted.

However, we observed no evidence for the conversion of Eu\(^{3+}\) to Eu\(^{+}\) from the X-ray absorption spectra of Eu ions in SrAl\(_2\)O\(_4\) doped with Eu\(^{3+}\) and Dy\(^{3+}\). Moreover, little difference can be found between the absorption spectra of Dy ions in the SrAl\(_2\)O\(_4\) doped with Eu\(^{3+}\) and Dy\(^{3+}\) before and after X-ray irradiation, although we observed bright and long-lasting phosphorescence after the X-ray irradiation. In addition, we observed that the valence states of Eu and Dy ions in the Eu\(^{2+}\)–Dy\(^{3+}\) doped glass sample remain unchanged after X-ray irradiation. Moreover, the photoluminescence spectrum, excitation spectrum, decay curve of phosphorescence and thermal luminescence curve in Dy\(^{3+}\)-undoped sample were observed to be nearly the same as those in the Eu\(^{2+}\)–Dy\(^{3+}\)-doped glass sample. Therefore, we suggest that Dy\(^{3+}\) and Eu\(^{2+}\) ions do not directly act as hole and electron traps.

Figure 5 shows electron spin resonance spectra of a 10ED glass samples fabricated in the reducing atmosphere.
glass sample after the UV light irradiation. Signals due to Eu**+ remained unchanged, while signals due to the formation of defects in the glass matrix were observed after the UV light irradiation and decayed with time. These results agree with the decay in phosphorescence.

We suggest that the mechanism of UV light induced long-lasting phosphorescence is that after irradiation by the white-color fluorescent lamp, electrons and holes forms in the samples. Part of the electrons is trapped by oxygen defects and part of the holes is captured by other defects in the glass matrix. Since the electron trap depth is broadly distributed and shallow, the electrons can be thermally released at room temperature and long-lasting phosphorescence is brought about.

Since long-lasting phosphorescence was observed in rare-earth-doped glass samples after UV light irradiation, we suspected that 3-dimensional long-lasting phosphorescence should be possible by irradiation of a focused ultrashort-pulsed laser via a multiphoton-related reaction.

Our study used regeneratively amplified 800 nm Ti:sapphire laser to emit 120 fs, 200 kHz, mode-locked pulses. The laser beam was focused by a 100 mm focal-length lens with the decay in the phosphorescence. Moreover, the phosphorescence spectrum after the excitation by the 250 nm UV light, the emission peaks in the wavelength region from 280 to 750 nm after the laser irradiation was observed for the Nd**3+-, Sm**3+-, Eu**3+-, Dy**3+-, Ho**3+-, Er**3+-, Tm**3+-, and Yb**3+-doped calcium alumino-silicate glass samples, while visible, bright, and long-lasting phosphorescence from the focused area was observed for the Ce**3+-, Tb**3+-, and Pr**3+-doped glass samples in the dark after the removal of the femtosecond laser. Figure 6 shows a photograph of emission states of phosphorescence in Ce**3+ (blue), Tb**3+ (green), and Pr**3+ (red) doped glasses. It was surprising that the phosphorescence could still be seen in the dark even one hour after the removal of the activating laser. The emission spectrum of the Tb**3+-doped glass sample had the same appearance as the phosphorescence spectrum excited by the 250 nm UV light. The emission peaks in the wavelength region from 350 to 600 nm can be ascribed to the 5d**→5f** (J=3, 4, f=1→6) transitions of the Tb**3+ ions. The intensity of the phosphorescence decreased with time, while the appearance of the phosphorescence spectrum remained unchanged. The intensity of the phosphorescence decreased in inverse proportion to the time, indicating the phosphorescence may be a decay process due to heat-assisted tunneling effect.

We observed broad absorption band peaking at 400 nm in the wavelength region from 280 to 750 nm after the laser irradiation. The band can be ascribed, for instance, to the absorption of aluminum-oxygen hole centers, which has been observed for UV irradiated CaO-Al**2O**3-based glass sample. The band fading at room temperature agrees with the decay in the phosphorescence. Moreover, the phosphorescence could only be observed in the laser focused area, where color centers were formed after the laser irradiation. Therefore, the disappearance of defects at room temperature is related to the decay of the phosphorescence. We estimated the time constant of the phosphorescence to differ from that of the decay of the absorbance due to laser-induced color centers. Consequently, phosphorescence and absorption may not be simply related; other factors should be considered.

We suggest that after the irradiation by the focused femtosecond pulsed laser, free electrons and holes formed in the glass samples through multiphoton absorption and successive multiphoton ionization, Joule heating, and collisional ionization processes. The holes or electrons were trapped by defect centers, released by heat at room temperature, and recombined with electrons or holes trapped by other defect centers. The released energy, due to the recombination of holes and electrons, was transferred to the rare-earth-ions and excited the electrons at the ground state to an excited state of the rare-earth-ions, finally, leading to the characteristic rare-earth-ion emissions.

5. Space-selective valence state manipulation of rare-earth-ions in glasses by a femtosecond laser

It is well known that laser light can be pulsed and focused to a spot of wavelength order. Ultrashort pulsed lasers have been used as powerful tools to clarify elementary processes, such as excitation-energy relaxation and both electron and proton transfer on nanosecond and picosecond time scales, that occur in a micrometer-sized area. Chemical-reaction mechanisms have also been elucidated for hydrogen atom transfer, isomerization reaction, and consecutive bond breaking by means of time-resolved laser spectroscopy. In addition, ultrashort pulsed laser can be used to make microscopic modifications to transparent materials. The reason for using this laser is that the strength of its electric field can reach 100 TW/cm**2, which is sufficient for inducing nonlinear optical effects in materials by use of a focusing lens, when the pulse width is 100 fs and the pulse energy is 1 µJ. The photoinduced reaction is expected to occur only near the focused part of the laser beam due to multiphoton processes.

We observed space-selective room-temperature permanent photoreduction of Eu**3+ to Eu**2+, and Sm**3+ to Sm**2+ in glasses by an infrared femtosecond laser. After irradiation by the focused infrared femtosecond laser for 1 s, a 10-µm bright spot was formed in the focused area of the laser beam in the Eu**3+-doped fluorozirconate glass sample, as observed through an optical microscope. We considered the spot to be the result of an increase of the refractive index at the center of the laser focus. Figure 7 shows the difference spectrum of the Eu**3+-doped fluorozirconate glass sample before and immediately after laser irradiation. For comparison, the absorption spectrum of the Eu**2+-doped fluoroaluminate glass sample is also shown in the figure. Compared with the absorption spectrum of the Eu**2+-doped fluoroaluminate glass sample, the broad band in the difference absorption spectrum of the Eu**3+-doped fluorozirconate glass sample can be ascribed mainly to the absorption that is due to the 5d→4f transitions of Eu**2+. ESR spectra of the Eu**3+-doped fluorozirconate glass sample before and after laser irradiation showed that no apparent signals were observed in the spectrum of the non-laser-irradiated Eu**3+-doped fluorozirconate glass sample, whereas apparent signals due to Eu**2+ and two signals at approximately 330 m T due to hole-trapped V**-type centers and to electrons trapped by Zr**4+ ions were observed in the spectrum of the laser-irradiated Eu**3+-doped fluorozirconate glass sample. Therefore, some of the Eu**3+ ions were reduced to Eu**2+ in the Eu**3+-doped fluorozirconate glass after laser irradiation.

Room-temperature permanent photoreduction of Sm**3+ to Sm**2+ was also observed in borate glass samples. After irradiation by the femtosecond laser, the focused area in the glass sample was orange as observed through an optical microscope. Figure 8 shows the photoluminescence spectra of the Sm**3+-doped glass sample before (a) and after (b) laser irradiation. The emissions at 560, 600, 645, and 705 nm in the unirradiated glass sample can be attributed to the 4f→4f transitions of Sm**2+. The four new peaks at 683, 700, 724, and 760 nm observed in the photoluminescence spectrum of the laser-irradiated glass sample can be attributed to the 4f→4f transitions of Sm**2+. Therefore, a part of Sm**2+ was converted to Sm**2+ after the laser irradiation.
Fig. 6. Photograph of the emission state of phosphorescence in Ce³⁺ (blue)-, Tb³⁺ (green)-, and Pr³⁺ (red)-doped calcium aluminosilicate glass samples after focused infrared femtosecond laser irradiation.

We consider the mechanism of the photoreduction of Sm³⁺ to Sm²⁺ after the femtosecond laser irradiation to be similar to the photoreduction of Eu³⁺ to Eu²⁺ in Eu³⁺-doped fluorozirconate glasses, while holes trapped by nonbridging oxygen ions and tetrahedral coordinated boron atoms in borate glasses.

Figure 9 shows the excitation spectra of the femtosecond laser-photoreduced part in an Sm³⁺-doped fluoroaluminate glass sample obtained by monitoring the ³D₄→⁷F₃ emission of Sm³⁺ before and after irradiation with the dye laser for 600 s. A hole was observed at 680 nm in the spectrum after the dye laser irradiation. No antihole or increased emission peak was observed around the hole. The results demonstrated the possibility of selectively inducing a change of valence state of Eu³⁺ (Sm³⁺) ions on the micrometer scale inside a glass sample by use of a focused nonresonant femtosecond pulsed laser. Whereas a three-dimensional optical memory has approximately 10¹³ bits/cm³ storage density, which means that data information can be stored in the form of a change in refractive index in a spot, optical memory using a valence-state change of rare-earth ions in a spot may have the same storage density and may allow one to read out data in the form of luminescence, thus providing the advantage of a high signal-to-noise ratio. Therefore, the present technique will be useful in the fabrication of three-dimensional optical memory devices with high storage density. Moreover, femtosecond laser-photoreduced Sm³⁺-doped glasses exhibited a photochemical spectral hole burning memory property. The microspot induced by the focused femtosecond laser inside a glass sample can be further used to store data information via the irradiation of laser light with different wavelengths.

Fig. 7. Difference spectrum (a) between absorption of Eu³⁺-doped fluorozirconate glass after and before femtosecond laser irradiation, (b) absorption spectra of Eu²⁺-doped fluoroaluminate fabricated under a reducing atmosphere.

Fig. 8. Photoluminescence spectra of Sm³⁺-doped sodium aluminoborate glass before (a) and after (b) femtosecond laser irradiation (excitation source from Ar⁺ laser at 514.5 nm).

Fig. 9. Excitation spectra of the femtosecond laser-photoreduced part in a Sm³⁺-doped fluoroaluminate glass sample obtained by monitoring the ³D₄→⁷F₃ emission of Sm³⁺ before (a) and after (b) irradiation with the dye laser for 600 s.

Fig. 10. Various structures induced by the infrared femtosecond laser pulses.
wavelengths. As a result, the data information can be read out in the form of spectral holes. Sm$^{2+}$-doped glasses could become an ultimate optical memory device with an ultrahigh storage density.

6. Formation of rare-earth-ion-doped optical waveguide by using focused femtosecond laser

Considerable research has been carried out on the writing of Bragg gratings inside optical fibers.$^{3,30,38}$ The reaction between light and glass is usually induced by irradiating an area in a glass to achieve various types of light-induced structural changes. It is difficult to produce an interaction effect between glass and light by a one-photon process when the wavelength of excitation light differs from the resonant absorption wavelength of the glass. However, as shown in Fig. 10, various structures can be produced by using pulsed laser operating at the non-resonant wavelength with pulse widths of the order of femtoseconds: colored line due to the formation of color center, refractive index spot due to densification and defect formation, microvoid due to remelting and shock wave, microcrack due to destructive breakdown, etc. An increase in refractive index has been observed in an irradiated area in silica or germanium-doped silica glass samples with focused femtosecond laser pulses.$^{30}$ It was found that the irradiated region could function as an optical waveguide.

We also fabricated permanent damaged lines in various rare-earth-ion-doped glass samples by focusing 120-fs pulses from a regeneratively amplified Ti sapphire laser through a microscope objective lens and translating the glass samples parallel to the axis of the laser beam. Figure 11 shows the cross section and side view of the damaged line. Continuous line was induced after the scanning of the focused laser beam. Figure 12 shows the intensity distribution of the far-field at 800 nm for a laser-written damaged line. The laser-induced damaged line functions as a single-mode optical waveguide. We are still evaluating the transmission attenuation and light amplification property.

7. Conclusion

We have introduced the basic research concept of realization of novel optical functions of glass by combining an external electromagnetic field induced electron structure and rare-earth-ions. We reviewed the mechanisms and applications of photostimulated luminescence induced by X-ray; long-lasting phosphorescence induced by ultra-violet light and infrared femtosecond laser; space-selective manipulation of the valence state of rare-earth-ions; and formation of rare-earth-ion-doped optical waveguide for light amplification by using a focused infrared femtosecond laser. By using composite electromagnetic fields such as a laser coherent field, it is possible to effectively induce permanent and periodical structures in glasses which result in the realization of novel optical functions. We have confirmed that the proposed concept will open new possibility in the realization of novel optical functions for glass.

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References

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