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Novel Rare Earth Ions Doped Oxide Glasses for Amplifiers in Optical Fiber Communication Systems
新型稀土摻雜光纖通信放大器用氧化物玻璃的研究

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Abstract

Due to the rapid development of the wavelength division multiplexing (WDM) systems and optical networks, it is important and useful to explore new wavelength resources beyond the present C-/C+L-band served by EDFAs, and Thulium (Tm^{3+}) and Praseodymium (Pr^{3+}) have been proposed and confirmed as optical signal amplifiers at the S-band (1.46-1.53 μm) and O-band (1.26-1.36 μm), respectively. However, there remains a spectral gap at around 1.4 μm wavelength, at which hydroxyl (OH^-) impurity causes additional losses. Recently, the production of dry optical fibers enables the possibility to utilize this wavelength region. This progress also paves ways for the investigations on the ultra-short wavelength region around 1.2 μm wavelength where the loss is still low, and superbroadband luminescence/amplification covering the expanded low-loss window entirely.

In this thesis, Holmium (Ho^{3+}) doped gallate bismuth lead (GBL) glasses were prepared, and intense near-infrared (NIR) emission at 1.38 μm wavelength from the Ho^{3+}: $(^5S_2,^5F_4)\rightarrow{}^5I_5$ transition was obtained. Observation of this emission is primarily due to the low phonon energy (~535 cm^{-1}) of GBL glass matrix, which imposes suppression on the non-radiative decay that would occur on the emission manifolds ($^5S_2,^5F_4$). The stimulated emission cross-section was calculated to be 2.4×10^{-21} cm^2. Population inversions between the ($^5S_2,^5F_4$) and $^5I_5$ levels have been achieved, and a broad gain bandwidth from 1.35 to 1.45 μm was obtained. The large product of emission cross section and measured lifetime also support this characteristic.

Optical amplification at around 1.2 μm wavelength region can improve further the information traffic by utilizing dense WDM, and Ho^{3+}: $^5I_6\rightarrow{}^5I_8$ transition has been investigated in generating emission within this wavelength region. This transition needs

low phonon energy host matrix because of the narrowly spaced energy level $^5I_6$ to $^5I_7$. Intense Ho^{3+} 1.2 μm emission was recorded in both the lithium barium bismuth lead and germanium tellurite glasses due to their low phonon energies (<800 cm^{-1}). Yb^{3+} has been incorporated to further sensitize this emission, and the quantum efficiency was increased more than 3 times compared with Ho^{3+} singly doping. It has been demonstrated that the matrix phonons enable the energy transfer from Yb^{3+} ($^2F_{5/2}$) to Ho^{3+} ($^5I_6$) to occur easily. Similar emission was observed in Ho^{3+}-Yb^{3+} codoped germanium tellurite glass fibers that were fabricated using rod-in-tube method.

Considering that the Ho^{3+} 1.2 μm emission requires low phonon energy on the host materials, we propose the Tm^{3+}: $^1G_4 \rightarrow {}^3H_4$ transition as a potential alternative to yield 1.2 μm emissions, because this transition is less dependent on the host owning to the large energy gap between the $^1G_4$ and the next lower level. Efficient emission around 1.2 μm wavelength has been observed, and a positive gain band extending from 1.20 to 1.28 μm was achieved at relatively low concentration Tm^{3+} doped tellurite glasses under blue wavelength excitation. To improve further the population inversion at higher Tm^{3+} concentration, rare earth acceptors Terbium (Tb^{3+}) and Europium (Eu^{3+}) are incorporated. The population inversion was enhanced by depleting the terminal $^3H_4$ level through the cross relaxations $Tm^{3+}[^3H_4\text{-}{}^3H_5]$:$Tb^{3+}[^7F_6\text{-}{}^7F_3]$ and $Tm^{3+}[^3H_4\text{-}{}^3H_5]$:$Eu^{3+}[^7F_0\text{-}{}^7F_5]$.

Concerning the broadband emission locates at the third window (1.4-1.7 μm), Tm^{3+}-Er^{3+} codoped GBL glasses were prepared and characterized optically. The full-width at half-maximum (FWHM) of the relevant NIR emission band depends on the Tm^{3+}-Er^{3+} concentration ratio ([Tm]/[Er]), and a maximum FWHM of 165 nm was achieved when the concentration ratio was 4, and the line-shape characteristic of the broadband emission remains unchanged under a fixed concentration ratio $[Tm^{3+}]/[Er^{3+}]=4$. The energy transfer processes responsible for the flat broadband

emission have been confirmed due to the $Tm^{3+}[^3H_4\text{-}^3F_4]$:$Tm^{3+}[^3H_6\text{-}^3F_4]$ and $Tm^{3+}[^3H_4\text{-}^3F_4]$:$Er^{3+}[^4I_{15/2}\text{-}^4I_{13/2}]$. Further investigation on the energy transfer with assistance of matrix phonons shows that the matrix phonons play a crucial role in bridging the energy gap in the energy transfer process.

Superbroadband emission covering the wavelength range from 1.0 to 1.7 μm has been obtained by utilizing Tm-Bismuth(Bi) codoping scheme in germanate glasses, with intense complimentary emission around 1.3 μm wavelength contributed by the active Bi ions. Efficient energy transfer from active Bi to Tm^{3+} ions with efficiency as high as 67.7% was achieved which is beneficial for achieving flat broadband lineshape. The large stimulated emission cross-section and measured lifetime confirm the potentials of Tm-Bi codopants as luminescence sources for superbroadband NIR optical amplifiers and tunable lasers. Planar and channel waveguides were fabricated successfully in the Tm-Bi cocodoped gallogermanate glasses using K^+-Na^+ ion-exchange together with a standard micro-fabrication process and wet chemical etching method.

Superbroadband emission covering 1.25-1.68 μm wavelength region has also been obtained in Pr^{3+}-singly-doped bismuth gallate glasses. This emission originates from the two transitions $^1G_4 \rightarrow {}^3H_5$ and $^1D_2 \rightarrow {}^1G_4$, and is due to the extremely low phonon energy (~690 cm^{-1}) and the unique ligand field of the bismuth gallate glasses. The results confirm that other than Bi, Chromium (Cr), Nickel (Ni) and other chemical elements, Pr^{3+}-singly-doped system is a promising alternative in achieving superbroadband NIR emission.

To summarize, this thesis presents a systematic investigation on novel rare earth ions doped oxide glasses for optical amplifications operating at both specific and superbroadband wavelength regions in the expanded low-loss transmission window. In particular, the preparations of fibers and planar waveguides based on these glasses confirm their potentials in practical applications.

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