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SINGLE CRYSTAL MATERIALS AS OPTICAL AMPLIFIERS

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ABSTRACT

Optical amplifiers with gains of 30dB at 1.55\(\mu\m\) have been demonstrated using erbium doped silica fibers. Unfortunately, the incorporation of other rare-earth ions such as Nd in silica fibers for amplification at 1.31\(\mu\m\) has been unsuccessful. Single crystal materials represent an interesting alternative as optical amplifiers at this wavelength. An estimate of gains for single crystal systems is calculated for specific examples and path lengths of 1mm-100cm are estimated. Host lattices as well as dopants appropriate for amplification at 1.31\(\mu\m\) are emphasized.

INTRODUCTION

Amplification is an important part of optical fiber communications. Possible applications for amplifiers include repeaters to amplify signals after fiber losses, optical receiver preamplifiers, or optical gain blocks to compensate for losses in splitting networks. While some of these needs can be met by electronic amplifiers, optical amplifiers offer greater simplicity, greater flexibility, and better performance, especially in network related applications. Ideally, amplifiers at 1.31\(\mu\m\) and 1.55\(\mu\m\) are needed since these two wavelengths are commonly used in optical communications. Several different types of optical amplifiers have been discussed including Raman fiber amplifiers[1], doped fiber amplifiers[2,3], and semiconductor laser amplifiers[4].

Recently, a tremendous advance has occurred in the field of Er-doped fiber amplifiers[5-7]. This technology involves the incorporation of low levels of Er\(^{3+}\) ions in a silica fiber. The fiber can be pumped with a diode laser at 0.98\(\mu\m\) or at 1.48\(\mu\m\) and fluorescence from the \(^{4}\text{I}_{13/2}\) to the \(^{4}\text{I}_{15/2}\) levels occurs at 1.53-1.56\(\mu\m\) (Figure 1a,b). When this fluorescence is stimulated by a signal from an optical network, emission is induced at that wavelength resulting in amplification of the network signal (Figure 1c). This system can be optimized for dopant concentration, fiber length, and pump power. Typical fiber lengths are a few meters to a few kilometers with dopant levels ranging from percents to 10ppm. To date, devices with gains as high as 30-40dB have been produced.
While Er-doped silica fibers work well for optical gain at 1.55\(\mu m\), attempts to extend this technique to amplification at 1.31\(\mu m\) have been unsuccessful. The rare-earth ion of choice for amplification at 1.31\(\mu m\) is Nd\(^{3+}\) which has a transition at 1.32\(\mu m\). Fiber amplifiers of Nd-doped silica have several shortcomings: a) the primary fluorescence for Nd is at 1.06\(\mu m\) instead of 1.31\(\mu m\), b) the transition at 1.32-1.36\(\mu m\) does not include 1.31\(\mu m\) typical of communications networks, and c) the output is limited by excited state absorption (ESA) [8]. Attempts to use glasses other than silica have shown limited success[9].

The requirements for a successful amplifier are very similar to those of a laser, i.e. large population inversion, large absorption cross-section, and large emission cross-section. This suggests that a single crystal device may be a suitable alternative to a glass-based fiber amplifier. Of course, single crystal amplifiers will only be viable if the length scale is short (on the order of centimeters not meters). Below, we estimate the gain of single crystal optical amplifiers and give examples of particular systems that may be of interest for amplification at 1.31\(\mu m\).

**LENGTH REQUIREMENTS**

For an electromagnetic wave (in the small signal limit) propagating linearly in a pumped laser medium of infinite extent, the intensity \(I(L)\) as a function of distance traveled \(L\) can, neglecting saturation effects, be expressed as

\[
I(L) = I(0) \exp \left[ \sigma_e (N_1 - N_2) L - \alpha L \right]
\]

in which \(\sigma_e\) is the emission cross section for the laser active ion, \(N_1\) (\(N_2\)) is the population density of laser ions in the upper (lower) energy level defining the laser frequency, and \(\alpha\) is the total attenuation from all sources of energy loss in the medium. From this expression the gain in dB follows as

\[
G (dB) = 4.34 \left[ \sigma_e (N_1 - N_2) - \alpha \right] L.
\]

In the most favorable circumstances \(N_1 = N >> N_2\) for four-level laser operation, where \(N\) is the total number of laser atoms per unit volume, and the attenuation \(\alpha\) (for optically pure hosts) is negligibly small. In this case the Eq.(2) can be simplified further to the form

\[
G (dB) = 4.3 \sigma_e N L.
\]

For a given laser ion the emission cross section \(\sigma_e\) is a function of the spontaneous transition rate \(A_{12}\) between the relevant laser levels 1 and 2, the associated vacuum wavelength \(\lambda_{12}\), the host refractive index \(n\), and the linewidth \(\Gamma\) of the spontaneous emission lineshape function according to

\[
\sigma_e \propto A_{12} \lambda_{12}^2 / (n^2 \Gamma).
\]

The above equations hold for both glass and crystalline hosts. In going from a glassy environment to a crystalline one, the dominant change in emission cross section occurs via a decrease in \(\Gamma\) of between a factor of 10 and 100 which results from the decrease in local environment disorder. It follows from Eq.(4) that the anticipated increase in \(\sigma_e\) and decrease in
propagation length L required for a specific gain G are both of this same order when the host is changed from glass to crystal.

Typical cross sections for laser ions in crystals are of order $10^{-19}$ to $10^{-18}$ (cm$^2$), while concentrations N for optimum laser operation are usually between 0.01 and 1 atomic percent ($=10^{18}$–$10^{20}$ cm$^{-3}$). It follows from Eq.(3) that propagation lengths L necessary to produce a gain of, say, 40dB, can be expected to be in the range of 1mm to 100cm. Although more realistic equations that incorporate some of the less than ideal realities pertaining to most actual laser mechanisms would somewhat increase these length estimates, it seems clear that the possibility of obtaining viable, crystal optical amplifiers with device lengths measured in cm (rather than in m or km) is not unrealistic.

In addition to gain, another important consideration in optical amplifiers is input pump power requirements. In the calculations above, complete inversion was assumed. In reality, population inversion will be dependent on the fluorescence lifetime with longer lifetimes requiring smaller pump powers for complete inversion. This lifetime is dependent on the laser system of the lasing ion and is relatively constant from host to host. Thus, for Er$^{3+}$ lifetimes are long (5-10ms) while Nd$^{3+}$ has a much shorter lifetime (500-800μs). This suggests that larger pump powers will be needed for Nd$^{3+}$ as compared to Er$^{3+}$.

**SINGLE CRYSTAL SYSTEMS**

Single crystal systems have several advantages over glass systems. The fluorescence wavelength and efficiency are dependent on both the coordination environment and oxidation state of the active ion in question. This is especially true in the case of transition metal ions. In some cases, the oxidation state of interest is not the most stable one for the ion involved. These requirements make the incorporation of these ions in glass fibers very unlikely. Even if the proper oxidation states could be obtained, the variety of coordination sites available in the amorphous host would be unfavorable for amplification. Also, the natural peak width in glasses is broader than in single crystals so that the peak fluorescence is higher in single crystals. Transition metal systems have broadened transitions that would be broadened even further if incorporated into a glass system. For these reasons, single crystal hosts must be considered.

**A. Neodymium Based Amplifiers**

The shortcomings of Nd-based fiber amplifiers may be surmountable in a single crystal system. Neodymium in single crystal hosts has been well studied. While the principal transition for this ion is always at 1.06μm the secondary transition near 1.3μm can be altered by choosing different hosts. For SrAl$_2$O$_9$ and 5NaF:9YF$_3$ this transition occurs at 1.3065 and 1.3070 μm, respectively. These values are much closer to the ideal 1.31μm than occurs in glass networks. Other oxide and fluoride systems that optimize the wavelength and branching ratio of the 1.31μm transition may be possible.

**B. Transition Metal Systems**
Unlike the 4f electrons of the rare earth ions, the 3d electrons of the transition metals are actively involved in bonding in transition metal compounds. This interaction provides correlation between the electronic and vibrational states of the transition metal ion and causes broadening of the fluorescence of these ions. This makes these systems attractive choices as tunable laser materials and may provide an interesting route to fluorescence at 1.31µm. This broadening should also insure a flat gain spectrum around the wavelength of interest. A notable example of these systems is Ti$^{3+}$ in sapphire (Al$_2$O$_3$) which has a broad fluorescence and exhibits tunable laser properties between 660-986nm[10]. Several transition metal systems have been reported to have broad fluorescence spectra which include 1.31µm. The details of these systems and other possible transition metals systems are outlined below.

Perhaps the best studied class of materials for tunable laser hosts in the IR are fluorides doped with transition metal ions. These hosts include MgF$_2$[11,12] and fluoride perovskites (AMF$_3$)[13]. These materials, have been doped with Cr$^{3+}$, V$^{2+}$, Co$^{2+}$, and Ni$^{2+}$. The wavelength coverage of these systems is summarized in Figure 2. It can be seen that for fluorescence at 1.3µm the ion of choice is V$^{2+}$. Brauch, et al.[13] have prepared samples of V$^{2+}$-doped CsCaF$_3$ by the Bridgman technique using vanadium crucibles as the dopant source. The volatility of CsF requires the use of a closed growth environment. These authors have found a lifetime of 1ms with a quantum efficiency of 40 percent at room temperature. We have prepared small crystals (1mm$^3$) by slow cooling samples sealed in Mo tubes with vanadium liners. Our results indicate that this system, when pumped at 457nm (1.42W), exhibits a broad fluorescence centered at 1.35µm and a lifetime of 1.1ms at 1.3µm. We have also investigated KCaF$_3$ as an alternate host. This compound is more stable than the Cs analog and is not subject to CsF volatility during synthesis. Initial results on the KCaF$_3$ host indicate a fluorescence peak at 1.25µm with a lifetime of 0.3ms (Figure 3).

Another fluoride system that may show fluorescence at 1.31µm is Ti$^{3+}$ in a fluoride host. To date, no such system has been reported but fluorescence of Ti$^{3+}$ in sapphire at 0.66-0.98µm combined with the general observation that fluoride hosts shift fluorescence to longer wavelengths suggests that Ti$^{3+}$ may exhibit fluorescence at 1.3µm in fluoride systems. Furthermore, Ti$^{3+}$ does not seem to suffer from excited state absorption which limits long wavelength fluorescence in Cr$^{3+}$. Two possible hosts worthy of investigation are SrAlF$_5$ and LiCaAlF$_6$ which have both exhibited laser activity when doped with Cr$^{3+}$[14,15].

Non-fluoride systems may also be possible hosts for optical amplifiers at 1.3µm. In particular, several oxides have been reported to exhibit fluorescence at this wavelength. One such materials is Cr-doped forsterite (Mg$_2$SiO$_4$). It is thought that the Cr in this system is tetravalent and substitutes for Si in a tetrahedral site[16]. This unusual oxidation state and site symmetry may explain the fluorescence wavelength of 1167-1345nm which is quite different than the range typical for Cr$^{3+}$ in oxide hosts (700-1000nm). The current drawback for this material as an amplifier is a short excited state lifetime (2.5µs). We have measured the fluorescence of Cr in yttrium orthosilicate (YOS), Y$_2$SiO$_5$, and find fluorescence near 1.3µm (Figure 3). In general, lifetimes of these Cr systems are quite short (10-20µs).
Divalent nickel in oxide hosts is another system which may show fluorescence at 1.3\textmu m. Previous results with Ni$^{2+}$ doped MgO indicate a fluorescence near 1.3\textmu m, however, this system suffers from excited state absorption[17,18]. Recently, broad band fluorescence centered at 1.3\textmu m has been reported for Ni$^{2+}$ in LiGa$_5$O$_8$[19] providing further evidence that this ion is of particular interest. We have studied other possible Ni$^{2+}$ hosts and have identified several compounds with fluorescence near 1.3\textmu m. These compounds as well as others we have investigated are summarized in Table 1.

**WAVEGUIDES**

A necessary feature of any optical amplifier is a waveguide to confine the light. For amorphous fiber amplifiers this technology is essentially the same as that for optical fibers. For single crystal amplifiers, the fabrication of waveguides is less well understood. Two possible waveguide structures are single crystal fibers and single crystal films.

Laser pedestal growth is a useful technique for the growth of small diameter single crystal fibers[20]. In this technique, the top of a source rod of a material to be grown is melted with a CO$_2$ laser and a single crystal fiber is pulled from this molten zone (Figure 4). This technique has the advantage that no crucible is needed, and the atmosphere surrounding the growing fiber can be controlled. Single crystal fibers with diameters as small as 50\textmu m have previously been demonstrated for several materials including YAG, Y$_2$O$_3$, Al$_2$O$_3$, and LiNbO$_3$[20,21]. Fiber lengths from 3-20cm have been reported depending on fiber diameter. In addition, the ability to clad these materials, either by the addition of a cladding or by diffusion, has been demonstrated. The disadvantage of this technique is slow growth rates and difficulty in maintaining constant diameters over long lengths.

An alternative to single crystal fibers is the use of a planar geometry. This involves the fabrication of a single crystal film. This technique has been demonstrated for amplification at 1.06\textmu m using Nd doped Y$_3$Ga$_5$O$_{12}$ (YGG) on a Y$_3$Al$_5$O$_{12}$ (YAG) substrate[22]. This study found that gain in single crystal films was one order of magnitude greater than that in amorphous films. This technique may be extended through the implantation or indiffusion of the ion of interest into undoped single crystal films of the host material. This technique may allow for longer path lengths than may be accessible in single crystal fibers.

**COUPLING LOSSES**

A significant hurdle in systems for optical amplification is coupling losses that occur between the device and the fiber network. In the case of silica fiber amplifiers this problem is greatly reduced by fusion splicing the two systems. For single crystal systems this solution may not be viable. There are two main factors that contribute to coupling loss: reflection loss and mode mismatch. The former is dependent on the relative refractive indices of the two systems. For fluoride systems the refractive index of the amplifier should be close to that of the optical fiber. For oxide systems, the difference in refractive index can generally be overcome by using index matching fluid or antireflection coatings as has been demonstrated in the case of lithium niobate. Mode mismatch can also be minimized by tailoring the waveguide of the amplifier.
Infusion losses as low as 1dB/cm have been achieved in lithium niobate[23].

SUMMARY

The potential advantages and disadvantages of single crystal hosts for use as optical amplifiers have been detailed. Transition metal ions have the advantage that the fluorescence wavelength is strongly dependent on host structure so that fluorescence may be tuned over a broad range of wavelengths. In particular, fluorescence at 1.31μm is accessible in a variety of materials. Furthermore, these systems may allow for pumping at different wavelengths than are accessible with rare-earth dopants (e.g. 800nm). Several different ions and host structure are possible including V$^{2+}$ in fluoride perovskites, Cr$^{4+}$ in oxides, Ni$^{2+}$ in oxides, or Ti$^{3+}$ in fluorides. These systems have the disadvantage that single crystal structures with long path lengths are harder to produce than amorphous fibers. In spite of this difficulty, the potential of single crystal systems warrants further investigation.

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REFERENCES


Figure 1. (a) The energy level scheme for Er$^{3+}$ with pump energy ($I_p$) and fluorescence energy ($I_o$). The resulting fluorescence spectrum is given in (b). In (c), a schematic of an optical amplifier is presented showing intensity gain.
Figure 2. Fluorescence wavelengths of solid state tunable laser systems.

Figure 3. Fluorescence measurements for V$^{2+}$-doped crystal of CsCaF$_3$, Ni$^{2+}$-doped LiGa$_5$O$_8$, and Cr$^{4+}$-doped Y$_2$SiO$_5$ (structure at 1.38$\mu$m is due to glass sample holder).
Figure 4. A schematic representation of the laser pedestal growth method for the production of small diameter single crystal fibers.