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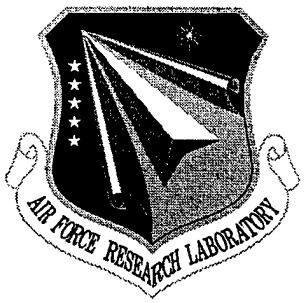

CO-DOPED OPTICAL FIBER LASERS

Hope Technologies, Inc.

T. F. Morse and J. M. Battiato

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13. ABSTRACT *(Maximum 200 words)*

Aerosol techniques for the incorporation of rare dopants into optical fiber preforms have been developed. This enables us to obtain liquid precursors that have a high degree of homogeneity at the molecular level, thus inhibiting phase separation in the final rare earth doped glass. This offers the possibility of convenient co-doping of optical fiber lasers using the Modified Chemical Vapor Deposition (MCVD) process. In this work, we describe how this process is utilized to study combinations of rare earth dopants, in particular, Nd and Er, so that lasing at discrete wavelengths may be obtained in the same cavity. This may have implications of new types of optical fiber gas sensors that are being developed. In addition, multiple cavity lasing can also be of interest for new classes of high power optical fiber lasers pumped by recently available stripe diodes.

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Abstract

Aerosol techniques for the incorporation of rare earth dopants into optical fiber preforms have been developed at the Laboratory for Lightwave Technology at Brown University. This enables us to obtain liquid precursors that have a high degree of homogeneity at the molecular level, thus inhibiting phase separation in the final rare earth doped glass. This offers the possibility of convenient co-doping of optical fiber lasers using the MCVD (Modified Chemical Vapor Deposition) process. In this work, we describe how this process is utilized to study combinations of rare earth dopants, in particular, Nd and Er, so that lasing at discrete wavelengths may be obtained in the same cavity. This may have implications for new types of optical fiber gas sensors that are being developed. In addition, multiple cavity lasing can also be of interest for new classes of high power optical fiber lasers pumped by recently available stripe diodes.

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ACKNOWLEDGEMENTS: T. F. Morse was responsible for the design and fabrication of the co-doped Nd/Er fiber. James M. Battiato designed and characterized the dual wavelength co-doped fiber laser.

Introduction: Aerosol Deposition and Co-Doping

In our efforts to obtain a means by which it is convenient to co-dope optical fiber lasers with rare earth elements, we have developed a process that, we believe, is the most "user friendly" technique for the fabrication of fiber lasers. The motivation for the development of this technique lies in the fact that all of the precursors for the incorporation of rare earth oxides into an optical fiber core have low vapor pressures. Thus, it is not possible to use the traditional liquid bubbler and oxygen as a carrier gas. Various techniques have been developed to circumvent this difficulty. These include using organic precursors (alkoxides of the rare earths) and heating up transport lines. This technique is really not suitable for co-doping one or more rare earth element, and non uniformity of temperature along the lines or in the MCVD substrate tube can give rise to axial nonuniformities in the fiber. In addition, such a technique does not lend itself easily to co-doping of more than one rare earth element. Another technique that is commonly used in the fabrication of rare earth optical fiber lasers is that of solution doping. In this process, an unsintered core is deposited in the preform substrate tube. The whole tube is then filled with a liquid solution in which the rare earth compound, usually in the form of a rare earth chloride, has been dissolved. The unsintered core consists of small, nanometer scale, "up-doped" amorphous particles that provide a large surface area that is coated by the rare earth chloride as the material is dried. At this point, the chloride is converted into an oxide, the small scale powders are then dried at moderate temperatures in the presence of chlorine gas to insure the removal of OH ions. Finally, the tube is collapsed and pulled into fiber. If there is a desire to include a phosphorous oxide in the final glass, this can be included in the solvent containing the rare earth chloride. This process, however, can lead to phase separated phosphorous regions in the final glass that can contribute to undesired scattering losses in the optical fiber.

The technique developed at the Laboratory for Lightwave Technology permits the convenient co-doping of optical fiber preforms. This involves aerosol transport of suitable precursor materials for the final oxide glass. Two routes are taken. In one, TEOS (tetra-ethyl ortho siloxane) is used as a solvent. This is an inviscid liquid available in 5 9's purity at a reasonable cost, since it is extensively used in the fabrication of silicon electronic materials. Into this liquid, we dissolve aluminum butoxide, a more viscous liquid, and the precursors of the rare earth oxides in the form of solid alkoxides. When this material is nebulized by a 1.5 mHz transducer, liquid particles, containing dissolved solid particles, are produced with a typical diameter of the order of a few microns. The aerosol size is so small that it can be transported through carrier tubes to the reaction zone in MCVD, and in other deposition processes as well. As a consequence of the fact that there is homogeneity at the molecular level, there is a greater tendency for complete mixing of ions in the final oxide glass. This may permit greater doping levels before the onset of

concentration quenching that diminishes laser performance as concentration increases. This aspect of aerosol doping is under study at the present moment.

Another technique that we have used to obtain low loss optical fibers is as follows. Since there can be solubility limitations on the amount of alkoxide that can be soluble in the TEOS, we have developed a transport process in which the silica is provided by Degussa Aerosil particles. This comes in the form of a silica powder of small size and high purity. With the silica already formed, we can use aqueous solutions, or solutions of de-ionized water in which we dissolve rare earth nitrates. With the nitrates there is no solubility limitation. When such material is used as a precursor in our aerosol nebulizer, the liquid aerosol droplet contains small silica particles, the solvent (water or alcohol), and the dissolved aluminum and rare earth material in the form of nitrates. This is transported into the substrate tube with an interior aerosol tube that is slaved to the moving MCVD burner. When the temperature reaches approximately 1200 centigrade, a reaction occurs to produce the rare earth doped silica in the form of a nano scale particle that is deposited on the wall. A Pt sting protrudes approximately 2 cm beyond the point at which the aerosol is injected. On the Pt sting we have 20,000 V, and the burner is grounded. For this arrangement, electrophoretic rather than thermophoretic deposition is the dominant mechanism of particle transport to the wall, and 100% deposition is achieved.

Reasons for Investigation of Co-Doping

Before proceeding to a specific case in which we have studied the co-doping of lasing ions in a single fiber, it is perhaps worthwhile to enumerate several situations in which such a configuration might be of interest.

The first of these is the case of the Yb-Er fiber laser. The erbium optical fiber laser has attracted more interest, research money, and commercial attention than all of the other fiber laser wavelengths combined. This is due to the fact that erbium has a lasing gain bandwidth that can go (depending on the complexity of the set-up) from 1522-1610 nm. This wavelength occurs at the minimum absorption loss of an optical fiber telecommunications system, so that multiplexing this laser to carry numerous channels (16 is standard, 80 have been done in the laboratory). The pump laser for the erbium fiber is either at 980 or 1480 nm. Both of these absorption bands are relatively narrow, so that an instability in the pump wavelength can result in a slight instability in the wavelength of the laser amplifier wavelength. With increasing WDM (Wavelength Division Multiplexing) applications, the stability of the laser becomes increasingly important. Ytterbium, if co-doped with erbium, can be pumped near 1.06 microns. Depending upon the specific nature of the glass host, the ytterbium can efficiently transfer its energy to the erbium. Since the ytterbium has a much flatter absorption spectrum, any variations in the pump source will have but slight detrimental influence on the ytterbium inversion, and thus, through phonon transfer, little effect on

the gain bandwidth of the erbium. This is the primary motivation in co-doping with a Yb-Er combination.

Another arrangement, also involving the Y-Er combination of recent importance, is that of the cladding pumped optical fiber. This is associated with the recent advances in laser stripe diodes that have the capability of power outputs into a multi-mode fiber of several tens of watts, and this value is constantly being increased. Ideally, we wish to take the multimode, large power output of such a device and focus it into the core of a single mode optical fiber. Thus, the optical fiber would serve two functions. First, it would be a mode converter in that the multimode output of the stripe diode would now be single mode, and second, it would serve as well as a wavelength converter to a longer wavelength. Such devices offer the promise of compact, high energy sources, with no bulk optics, and no water cooling. These can serve a host of uses that vary from the telecommunications sector to the use of such devices in materials processing.

The problem with the above described concept is that it is not possible to focus the laser energy into the small single mode core. This is a violation of the etendue, or brightness rule in which the Ax (N.A.)=constant. The area through which radiation passes A, and N.A. is the numerical aperture at that point. Thus,

$$(AxN.A.)_{diode} = (AxN.A.)_{fiber}$$

The limitations on the area of the fiber are associated with fiber size, flexibility, and mechanical strength. The numerical aperture of the fiber should be as large as possible. We are presently working on a new design for a very high numerical aperture on an all glass fiber.

In order to circumvent the restrictions of this brightness rule, Snitzer and co-workers at Polaroid have proposed the following concept. The preform is machined into an asymmetric slab configuration, with a single mode guiding core at the center, and then it is pulled with a low index (1.4) polymer coating. Thus, light can be focused into the glass preform that serves as a multimode guiding structure for the light from the stripe diode. As this light proceeds down the fiber, it is reflected back whenever it comes to the edge of the polymer. Thus, after some distance, it will have passed through the core and been absorbed by the core. This allows a way around the restrictions of the brightness theorem, and a high conversion to single mode energy. In essence, any helical modes that would spiral around the core will be reflected back into the glass to interact with the core. A typical length of such a fiber is of the order of tens of meters, since this length is required for all of the pump energy to be absorbed by the core. At the present time, such fibers are often pumped by Raman fiber lasers.

If the Yb-Er co-doped fiber laser can be made in an efficient cladding pumped configuration, this would have important implications for sattelite-sattelite space communications. We are also beginning work on the following concept.

In cladding pumped designs, the length must be long enough to insure that all of the pump radiation is absorbed. This means that the rays must cross the core many times before they are absorbed. Pumping from both ends can shorten the fiber length, but another concept is perhaps worthy of consideration. If a substrate tube doped with Nd, and Ge, for example, could be obtained, it would be possible to dope Yb-Er in the core. Thus the outer multimode structure could be made into a laser with 100% mirrors written into this cladding. This could be done with Bragg gratings chirped sufficiently to insure that all modes would be reflected. Thus, if pumped by 805 nm radiation from a stripe diode, the Bragg gratings would function as dichroic mirrors and confine the 1.06 micron radiation. This radiation would, in turn, pump the Yb in the fiber core, and this inversion would be transferred through lattice phonons to the Er. The core would contain 100% Bragg gratings at 1.1 microns to contain the Yb radiation, and Bragg gratings (100% at one end only) would be written into the core to form the cavity at 1.5 microns.

Unfortunately, there are no suppliers of such substrate tubes. In order to circumvent this problem, we are attempting to modify some of the sol-gel material that has been supplied to us by J. MacChesney of Lucent Technologies. This is a material that has been developed at Lucent for high purity overcladding tubes to enable the MCVD internal deposition technique to complete with the larger fiber boules that result from VAD or OVD. We have received material that is partially sintered, and we have made some preliminary attempts to infiltrate the partially sintered sol-gel overcladding tubes with Nd ions. A furnace given to us by Lucent Technologies has just been set up, and experiments to infiltrated the silica sol-gel tube are in process.

A Dual Wavelength Common Cavity Co-Doped Fiber Laser

In the following, we consider the specific behavior of a co-doped fiber laser. This material has been described in detail in a recent publication.
This laser is doped with erbium(Er) and neodymium(Nd), and two sets of fiberBragg gratings provide simultaneous lasing at 1069 nm(Nd) and 1550 nm(Er). In order to achieve this, excitation at two different pump wavelengths was required.

Some of the applications of multiple wavelength fiber lasers are wavelength division multiplexing (WDM), spectroscopy, and fiber optic sensors. Numerous techniques have been used to create multi-wavelength lasers in silica based fibers, and these techniques typically use either a common gain medium in a ring configuration or multiple coupled cavities with separate gain media in each.[1 2 3 4] A typical example would be a fiber doped with either Er or Nd. One approach toward forming a multiple wavelength fiber laser is to combine different rare earth dopants into the same fiber. We consider here a dual wavelength fiber laser that is formed with a common gain medium, a co-doped erbium and neodymium fiber, in a linear cavity. This fiber has been fabricated with the aerosol deposition

technique described above. One earlier demonstration of a multi-wavelength fiber laser using co-doped Er/Nd fiber used broad band mirrors and was pumped by an Argon laser.[5] In this present work, external mirrors are replaced by two adjacent pairs of fiber Bragg gratings. The fiber gratings thus act as alignment free mirrors. This serves to reduce coupling losses and creates a compact laser source with narrow line-width lasing at both 1069 nm and 1550 nm. The argon pump used previously is replaced by two pump sources in an attempt separately to pump the Er and Nd components of the fiber at 980 nm and 810 nm, respectively. These wavelengths are optimal for pumping Er and Nd and permit compact lasers diode sources to be used.

Part of the motivation in this work was to examine a tri-doped optical fiber, with Nd, Yb, and Er. It was speculated that it should be possible to pump the Nd at 805 nm, the inversion at 1,060 nm in Nd would pump the Yb, which would then, through lattice phonons, transfer energy to provide an inversion in the Er. Work is still continuing on this tri-doped system, but the emphasis on the following section are some experimental results that were obtained in the Nd-Er system.

Experimental Results on a Nd/Er co-doped fiber.

The experimental configuration is illustrated in Fig. 1. We have used an Er/Nd co-doped fiber, four fiber Bragg gratings (G1, G2, G3, and G4), a WDM element, and two pump sources. The fiber cavity was constructed by fusion splicing the co-doped fiber and two pairs of wavelength matched fiber Bragg gratings. Cavity lengths of 5, 15, and 20 m of the co-doped fiber were tested.

As noted above, the Yb/Er fiber was fabricated using an aerosol doping technique with Er concentrations of 200 ppm and Nd concentrations of 200 ppm.[6] The fiber had a numerical aperture of .11, a core diameter of 7.2 μm, and a cutoff wavelength of 1035 nm. The absorption loss of the fiber at 980 nm is 1106 dB/km and at 810 nm 1839 dB/km. Typical fluorescence spectra were observed at 1069 nm ($^4F_{3/2}$ ->$^4I_{11/2}$ transition), 930 nm ($^4F_{3/2}$ ->$^4I_{9/2}$ transition), and 1350 nm ($^4F_{3/2}$ ->$^4I_{13/2}$ transition) from the Nd ions pumped at 810 nm and at 1550 nm ($^4I_{13/2}$ ->$^4I_{15/2}$ transition) from the Er ions pumped at 980 nm. Fig. 2 shows the peak fluorescence of the Er component at 1550 nm and the Nd component at 1069 nm.

The fiber Bragg gratings G1 and G4 (Fig. 1) are wavelength matched with a center resonance at 1071 nm, a full width half maximum (FWHM) of 1 nm, and reflectivities of 84% and 52% respectively. Fiber Bragg gratings G2 and G3 are wavelength matched with a center resonance at 1556 nm, a FWHM of 1 nm, and reflectivities of 94% and 90% respectively. Each grating is 1 mm in length. A 980/810 nm WDM element was used to combine the two input sources which were pumped directly through gratings G1 and G2. The Er component of the fiber was pumped with a 980 nm laser diode while the Nd component was pumped with the 810 nm output of a Ti:sapphire laser. The spectral output of the fiber laser is observed on an optical spectrum analyzer.

Both pumps were approximately of equal power at 1069 nm and 1556 nm, and the fiber laser was made with 5 meters of co-doped fiber (Fig 3). Pumping with a single pump results in a single lasing wavelength output. When pumping with only 980 nm, a single output at 1556 nm from the Er inversion created. When pumping at only 810 a single output at 1069 nm was observed . In both cases, the output power of the lasing line decreased when the second pump was turned on and dual wavelength lasing resumed. The observed decrease in the 1556 nm output of Er in the presence of the 810 nm pump is shown in Fig 4a. Similarly, the decrease in the 1069 nm output of Nd in the presence of the 980 nm pump is shown in Fig 4b.

The output power of each pump was measured after the WDM and before grating G1 (Fig. 1) to test for any coupling between the two pump sources which could possibly account for the behavior exhibited in Fig 4. The power in each pump was measured with a monochrometer using only one pump, and then with only the second pump to detect any changes in power. No changes in output power or coupling between the pumps were detected.

Laser output power versus pump power measurements were then performed to examine the effects of the dual pumping. A monochrometer and detector were added after grating G4 at the output of the laser (Fig. 1) to select one of two lasing wavelengths and to filter out unabsorbed pump power.

The output at 1556 nm was measured as a function of 980 pump power first with the 810 nm pump source off and then repeated with the 810 nm pump on. The results in Fig. 5a show the that introduction of the 810 nm pump induces some losses in the Er system and changes the threshold and slope efficiency of the laser. We believe this behavior is most likely associated with known excited state absorption (ESA) in Er.[7]

Laser output power versus pump power measurements were then repeated for the Nd laser system. The output at 1069 nm was measured as a function of 810 pump power first with the 980 nm pump source off and then repeated with the 980 nm pump on. A similar change in the threshold was obtained (Fig. 5b). Since the system under study is complex and an energy transfer between Er and Nd ions in the co-doped fiber occurs, the same pump measurements were repeated for a singly doped Nd fiber laser. As shown in Fig. 6, singly doped Nd exhibited similar behavior in the presence of the 980 nm pump. One possible explanation for this loss in Nd is ESA at 980 nm.[8] Other mechanisms are possible and these are under investigation.

In conclusion, we have demonstrated a dual wavelength fiber laser constructed from co-doped Er/Nd fiber and fiber Bragg gratings. ESA effects due to the pumping scheme were observed. Despite the losses caused by the dual pumping scheme, lasing occurs simultaneously for both the Nd and Er components of the fiber. Such a dual wavelength laser as has been demonstrated here, provides a convenient source for dual wavelength based sensor systems easing the requirement for coupling different sources into the same fiber. Initial evaluation of the temporal stability of the laser output

power from long term measurements over several days show stability to within +/- 2%. A more detailed study of the temporal characteristics is currently in progress

We wish to acknowledge K. Teegarden, R. Erdmann, and E. Snitzer for helpful discussions on our dual lasing fiber.

Conclusions

In this effort we have used an aerosol technique for the doping of optical fiber lasers using MCVD to produce a series of co-doped optical fiber lasers. The applications of rare earth co-doping were considered. As a specific example, the lasing behavior at 1550 and 1060 nm was studied in detail.

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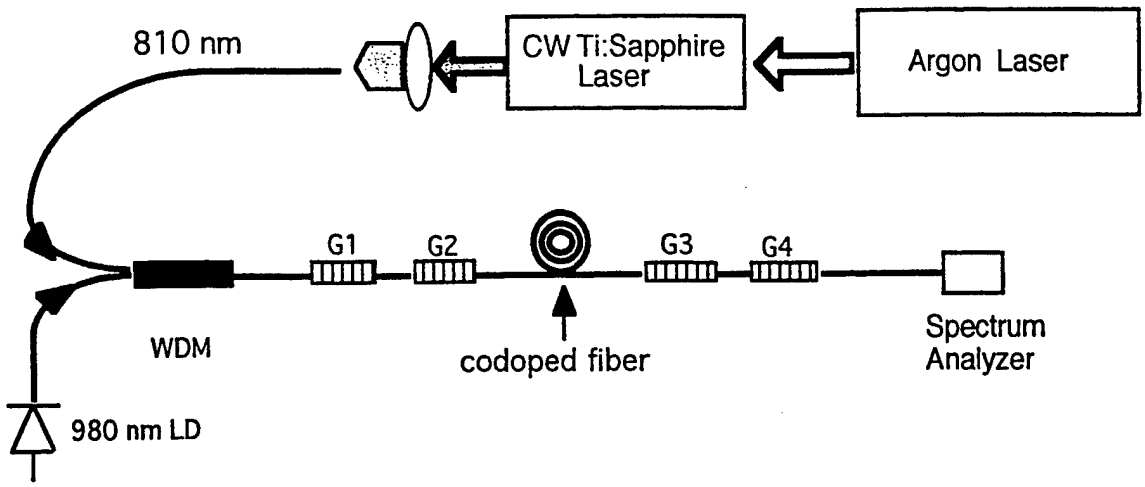


Fig. 1. Diagram of experimental setup. The common cavity fiber laser consist of Er/Nd co-doped fiber, four fiber Bragg gratings (G1, G2, G3, and G4), a WDM element, and two pump sources.

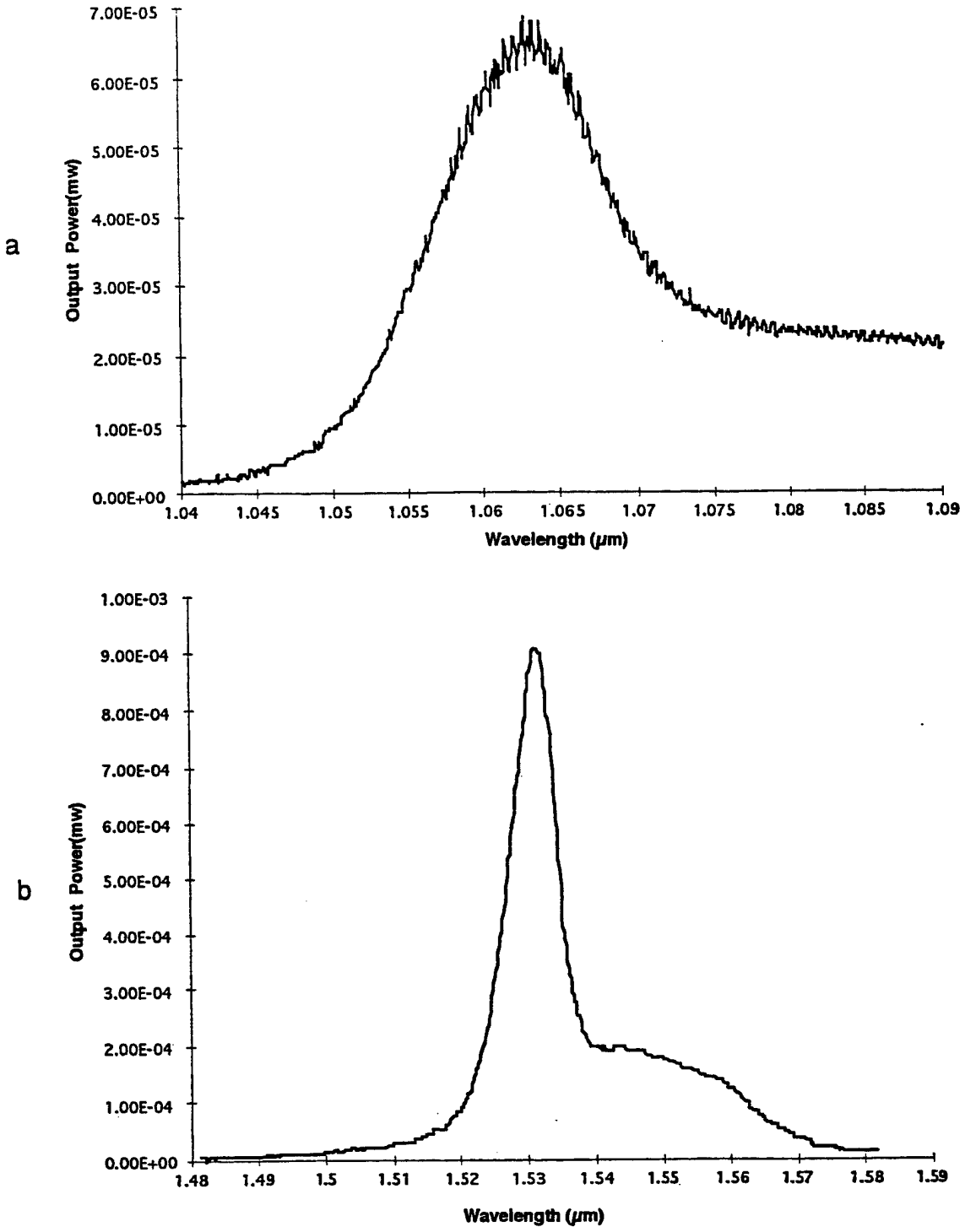


Fig. 2. Fluorescence spectra of Er/Nd co-doped fiber. (A) Peak output of Nd component pumped at 810 nm. (B) Peak output of Er component pumped at 980 nm.

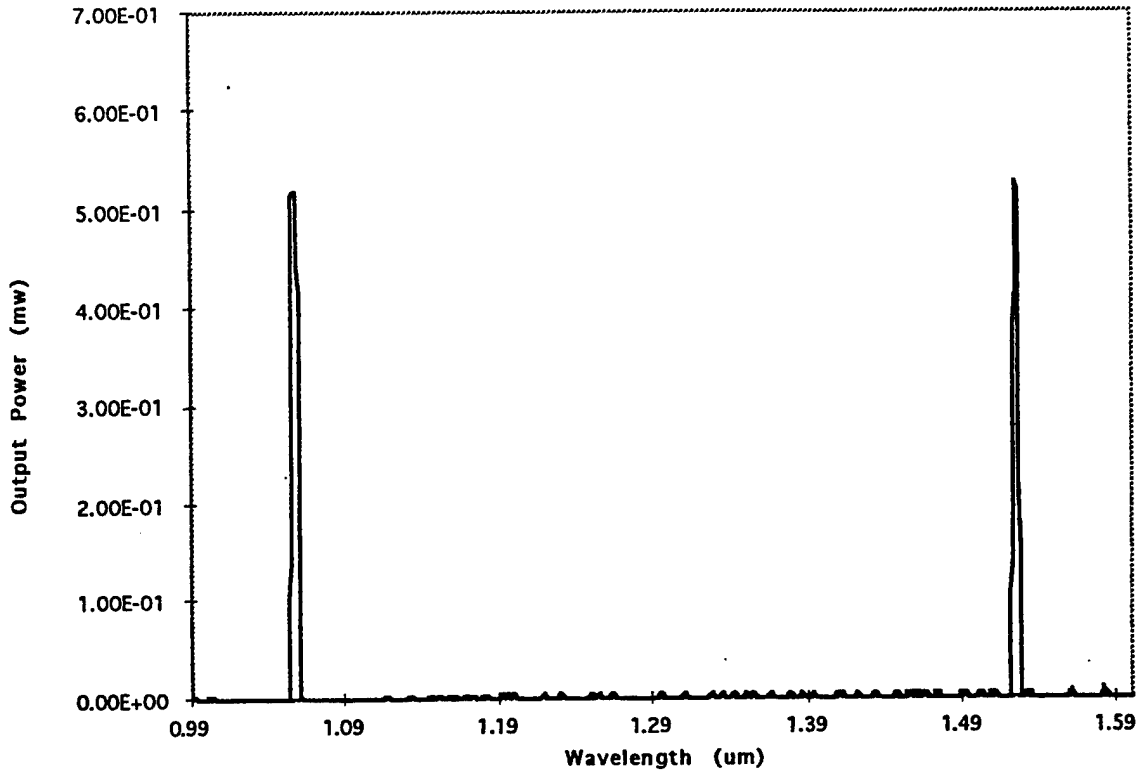


Fig. 3. Dual output at 1.069 μm and 1.55 μm from a fiber laser with 5 m of co-doped fiber.

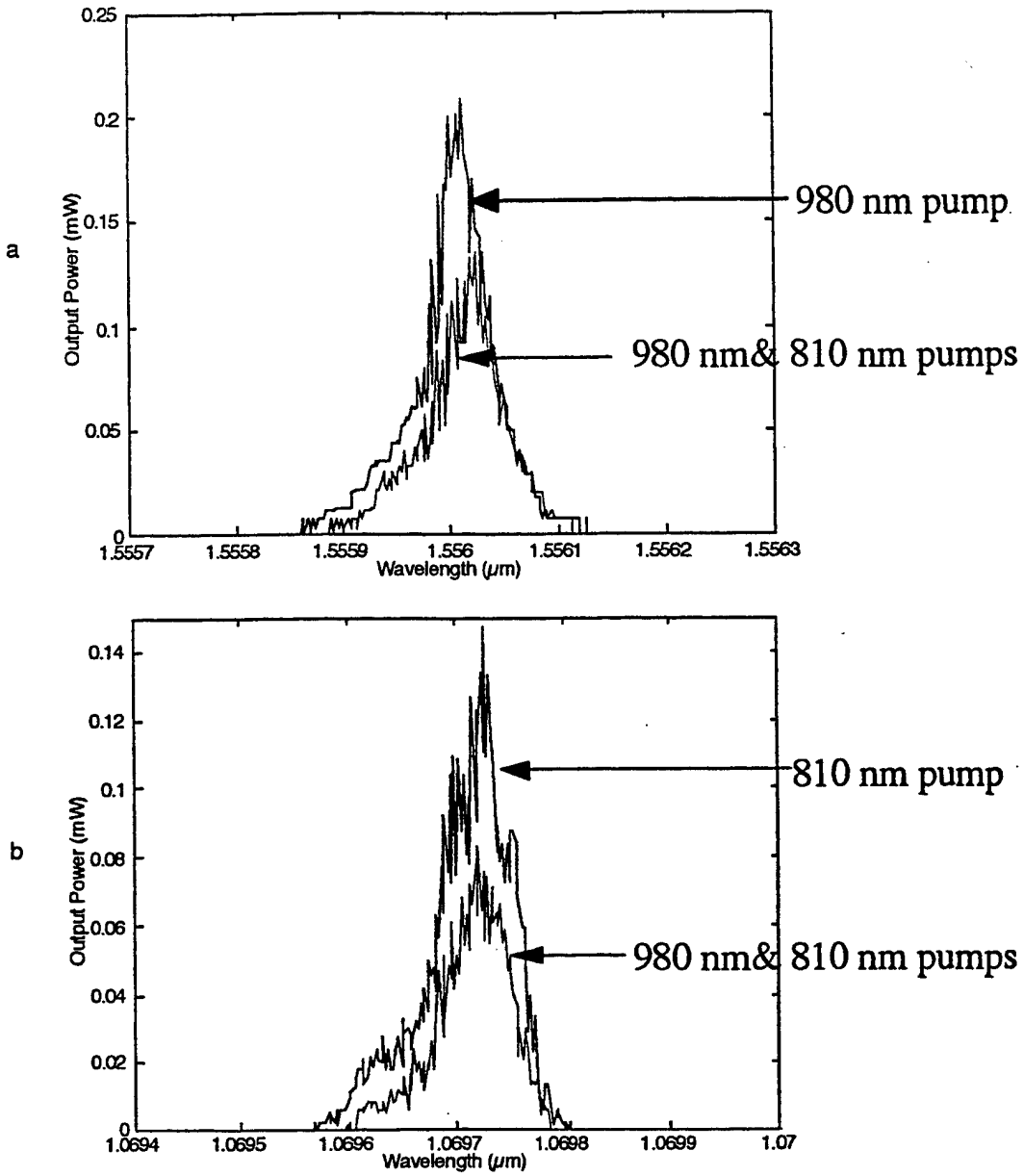
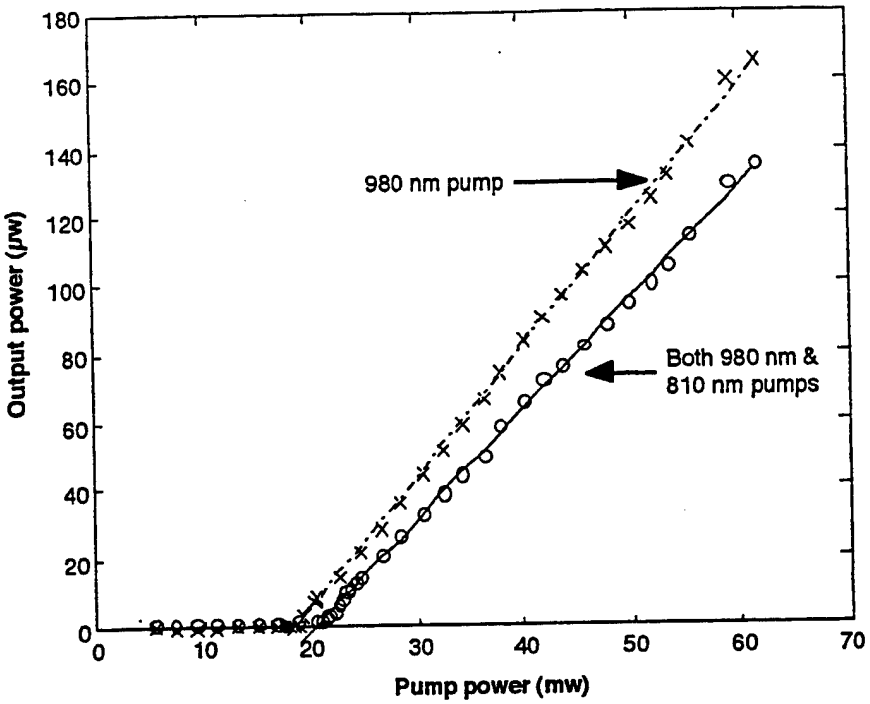


Fig. 4. (a). Output of 980 nm pumped Er component of laser with and without the 810 nm pump source on. (b) Output of 810 nm pumped Nd component of laser with and without the 980 nm pump source on.

a



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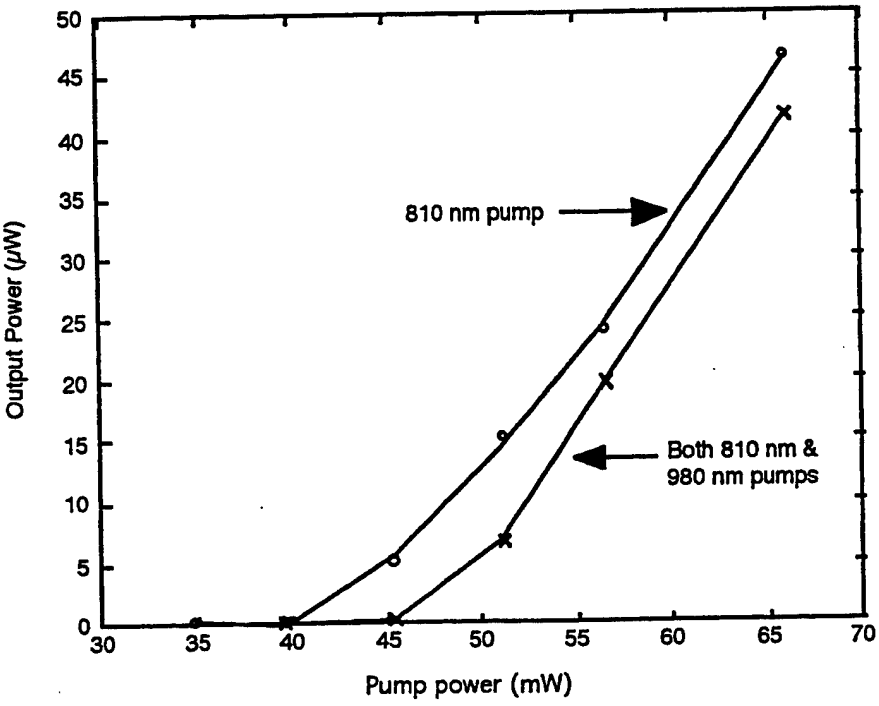

Fig. 5. Change in threshold for (a) Er component of laser at 1.55 μm with and without the 810 nm pump source on and (b) Nd component of laser at 1.069 μm with and without the 980 nm pump source on.

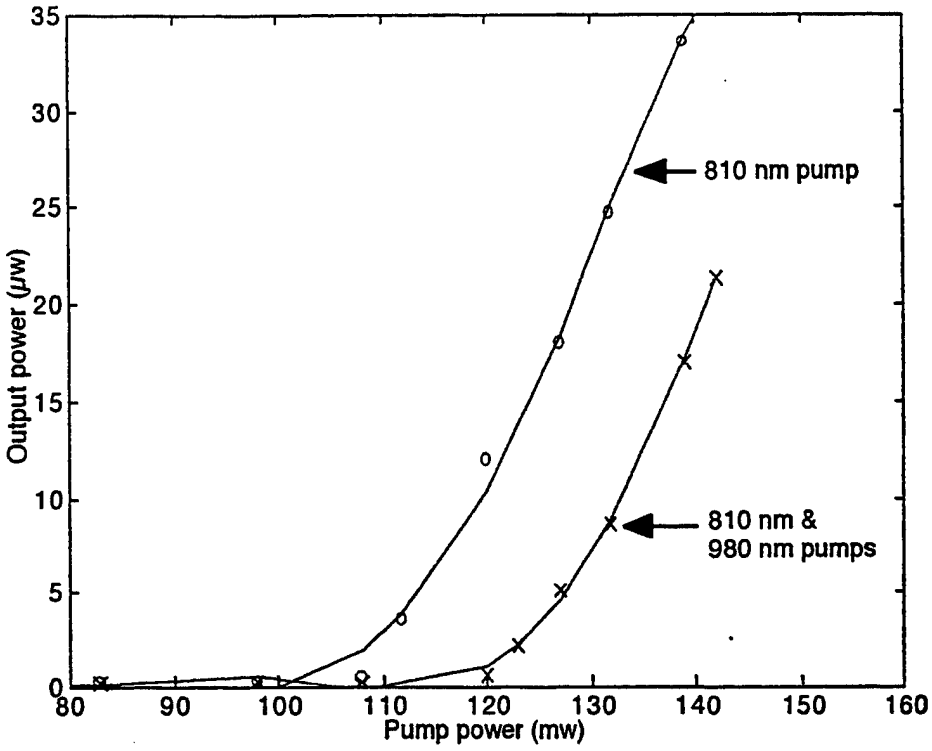

Fig 6. Change in threshold for a singly doped Nd fiber laser with and without a 980 nm pump source on.