

REPORT DOCUMENTATION PAGE

0415

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, gathering existing data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not have a valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 10/09/02		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 01/01/00 - 5/31/02		
4. TITLE AND SUBTITLE Advances in Fiber Lasers				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER F49620-00-1-0122		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) T.F. Morse				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Boston University 8 St. Mary's St. ECE/the Photonics Center Boston, MA 02215				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research				10. SPONSOR/MONITOR'S ACRONYM(S)		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT no restrictions DISTRIBUTION STATEMENT A Approved for Public Release Distribution Unlimited						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT A laboratory has been established in the Photonics Center at Boston University to investigate novel processes for high power optical fiber lasers, the performance of the lasers themselves, and various laser based optical fiber sensors. Work has been focused on a novel aerosol process for the fabrication of rare earth doped fiber lasers. We have recently proposed a new concept in laser cavity design that permits a large number of end pumping ports in a traveling wave configuration. This makes use of a yttrium vanadate polarizing prism used in conjunction with multiple gain sources, pumps and 1/4 wave phase retarders.						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:				17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON T.F. Morse
a. REPORT	b. ABSTRACT	c. THIS PAGE				19b. TELEPHONE NUMBER (include area code) 617-358-1035

20030106 106

Final Report for Grant F49620-00-1-0122
Advances in Fiber Lasers
January 1, 2000-May 31, 2002
Laboratory for Lightwave Technology
ECE/The Photonics Center
Boston University

T.F. Morse, Professor of Engineering

Introduction

In June, 1999, the Laboratory for Lightwave Technology moved from Brown University to the Photonics Center, Boston University, where T.F. Morse became a Professor of Electrical and Computer Engineering. The laboratory established at Boston University was the largest Boston University laboratory up to that time, involving over 3,500 square feet of laboratory space. All of the equipment from a similar, but smaller laboratory was brought from Brown University. In addition, a new Nextrom MCVD system was obtained through the use of Air Force funding and the efforts of Nextrom. This represents a state-of-the-art system for the MCVD fabrication of optical fiber preforms. In addition, through a donation from Lucent Technologies, of Norcross, Georgia, a new 8 m optical fiber draw tower was obtained. The draw tower was originally intended for use in pulling tubes for device packaging, but it was never used. Additional funding was obtained to outfit this with new Nextrom fiber pulling equipment.

The laboratory contains the most advanced fiber processing equipment of any U.S. university. A major part of the effort was the establishment of this laboratory, which, perhaps not unexpectedly, took longer than expected. The different components of the laboratory are associated with preform processing, fiber drawing, and fiber and fiber device characterization.

A. Processing

There are three techniques for the fabrication of optical fiber preforms. One of these is an internal process in which doped silica is deposited on the inside of a high quality silica substrate tube. This is MCVD (Modified Chemical Vapor Deposition). Layers are sintered after deposition, and a core layer contains an index-raising component, usually germanium. We have one SGC (Special Gas Controls) MCVD lathe that has been modified for our aerosol technique, to be described below, and this is shown in Figure 1. In addition, we have a state-of-the-art MCVD processing system from Nextrom (formerly a subsidiary of Nokia). This is shown in Figure 2. We have entered into a collaborative research agreement with Nextrom, and our laboratory is being used as a research facility for fiber fabrication in conjunction with Nextrom. MCVD is the process by which approximately 40% of the optical fibers in the world are fabricated.

In addition to two MCVD systems, we have an OVD (Outside Vapor Deposition, pioneered by Corning) lathe that was donated by Bell Laboratories. In this process, a target rod moves back and forth over a "soot" producing flame. As the build-up on this target

DISTRIBUTION STATEMENT A

Approved for Public Release
Distribution Unlimited

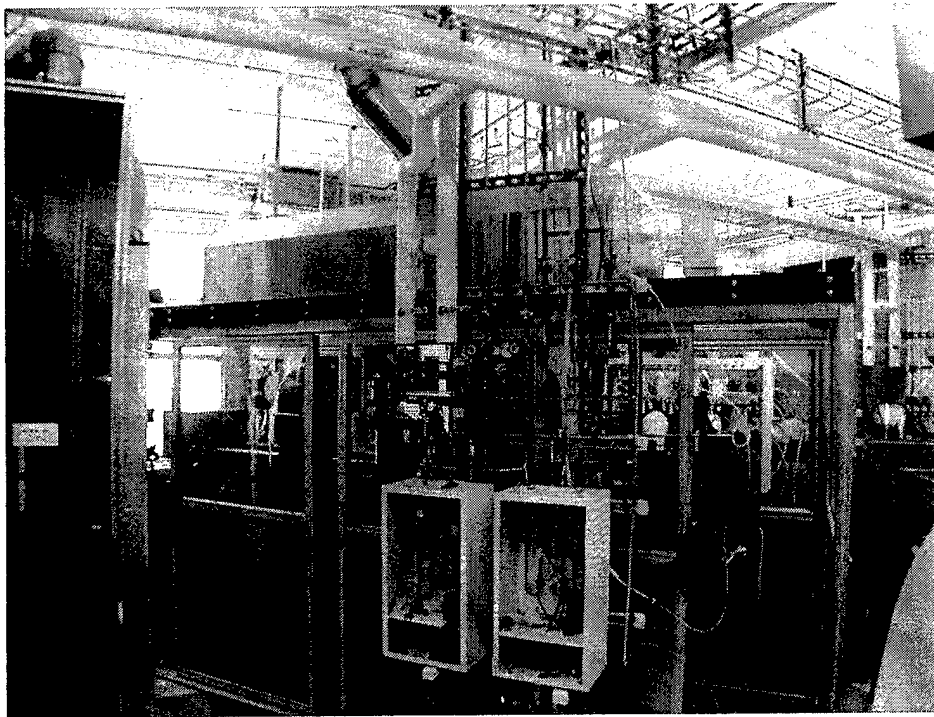


Figure 1. SGC MCVD system

Rod increases; the precursor constituent flow rates are changed to provide the desired index gradation. Subsequent processing sinters the soot boule into a vitreous preform

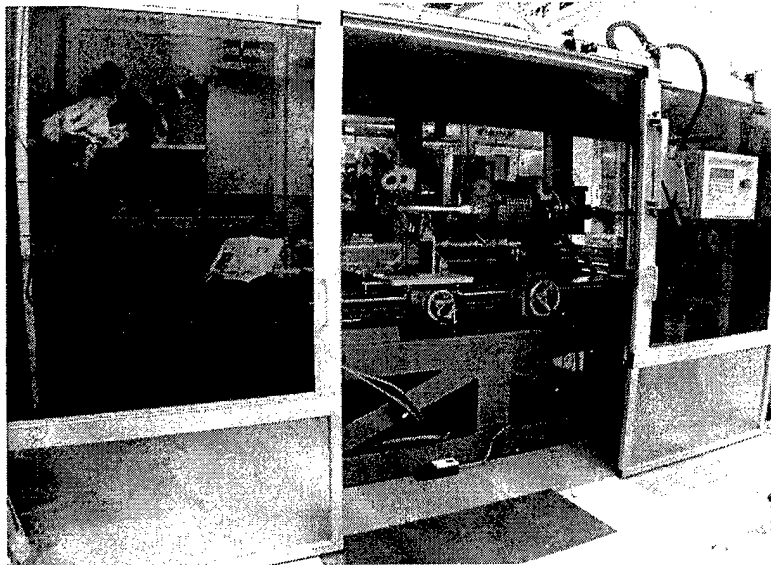


Figure 2. Nextrom MCVD system

preform that is then pulled into fiber. This is a more complex process than MCVD. However, as we hope to demonstrate in this proposed research, the use of OVD in

conjunction with aerosol deposition of new glasses for low scattering loss fibers is the only possible approach. This is a consequence of the wide palette of precursors available through organo-metallics. The OVD lathe in our laboratory is shown in Figure 3.

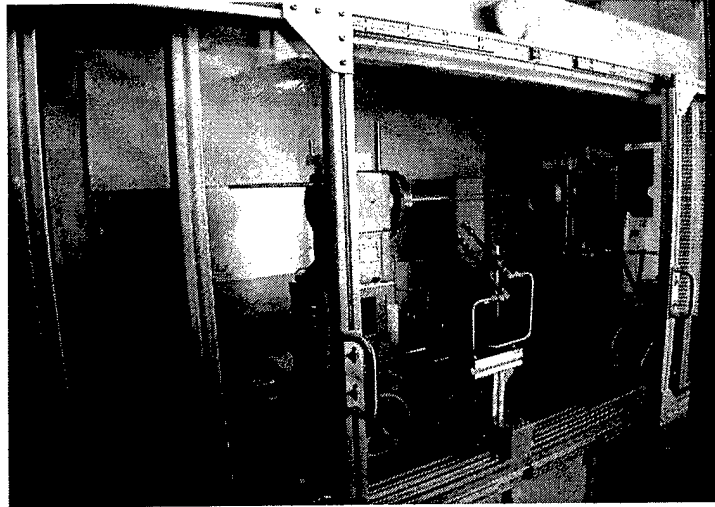


Figure 3. OVD system

B. Optical Fiber Draw Tower

Another main component of our fiber processing capability is an 8 m state-of-the-art optical fiber draw tower. This is shown in Figure 4. It has a 60 W carbon resistance furnace capable of drawing preforms up to 5 cm in diameter. The tower frame and feed mechanisms were a donation of Lucent Technologies, Norcross, Ga, and the tower was recently outfitted with new winding equipment from Nextrom. Precision fiber measuring equipment with sophisticated feed-back allow the precise drawing of fiber in diameters that range from 40 microns up to several hundred microns. The coating system uses a dual-coat procedure with two high intensity UV lamps to cure the polymer.

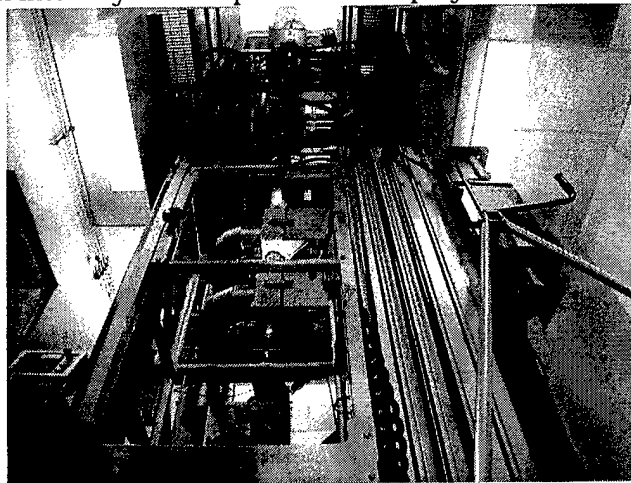


Figure 4. Nextrom optical fiber draw tower

D. HF Washer, Scrubber

There are two other important pieces of equipment needed for fiber processing: 1) a scrubber unit capable of removing chlorine in traditional fiber processing. (The proposed research here eliminates chlorine as a by product of the processing); 2) an HF washer to reduce the size of the preform in order to be able to obtain a desired NA and fiber diameter. This is needed to ensure that the fiber is single mode at the proper wavelength. Another important aspect of our processing infrastructure is a first floor room containing 12 large cylinders of hydrogen. This gas is piped up to the fifth floor laboratory with all of the necessary protection of double walled stainless steel pipes as well as a sensor system to detect any hydrogen leaks.

E. Characterization

The measurements we typically perform on preforms and fibers are: preform refractive index, fiber attenuation, and fiber mode field diameter. In the case of fiber lasers, we also measure lifetime to obtain information on clustering effects. The equipment for preform refractive index profile is a York Technology P102 which we hope to replace in the near future with a newer unit.

F. Fiber Device Laboratory

Our fiber device laboratory is shown in Figure 5. This contains five optical benches, a Coherent Radiation FreD laser (frequency doubled 488 nm argon ion laser that operates at 244 nm). This laser permits the writing of Bragg gratings in photosensitive fibers using phase masks. We have been working with a start-up company, Optical Switch, and they have made use of our facilities to test their new process for the fabrication of phase masks. We have a main frame argon ion laser that is used to pump a Ti:Sapphire laser that then pumps laser fibers. In addition, which is an important aspect of our program in high energy fiber lasers, we have two Boston Laser Polychrome fiber-connected diode pump sources. These are at 915 nm, with a numerical aperture of 0.22 in a 200 micron all-glass fiber, and a power output of 40 W. We also have two pump sources from Spectra Physics lasers. These are each 35 W, fiber coupled, with a 200 micron fiber and a numerical aperture of 0.45. These fibers are coated with a low index polymer. Miscellaneous equipment in this laboratory also contains several spectrum analyzers, and other optical measuring equipment.



Figure 5. Optical fiber device laboratory

Aerosol Processing, Double Clad Fiber Lasers

We have continued to develop an aerosol technique for the processing of optical fiber lasers, and we consider this to be the most flexible technique for fiber laser fabrication. An aerosol of organometallic liquids is made into which the solid rare earth precursors (acetyl-acetonate, rare earth beta-diketones, and alcoxides) are dissolved. A 1.6 MHz transducer nebulizes this mixture containing dissolved solids, and homogeneity is obtained at the molecular level, in contrast with solution doping. This aerosol is depicted in Figure 6, and in Figure 7 is shown the schematic of its use in the MCVD process.

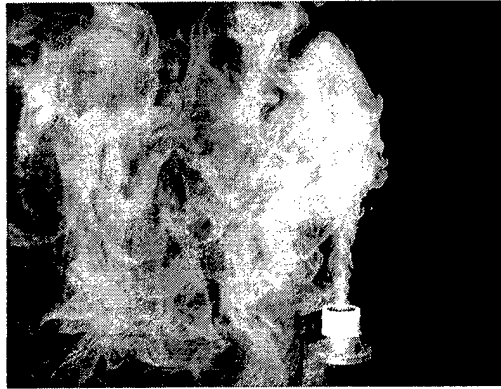


Figure 6. Aerosol generation with 1.6 MHz transducer

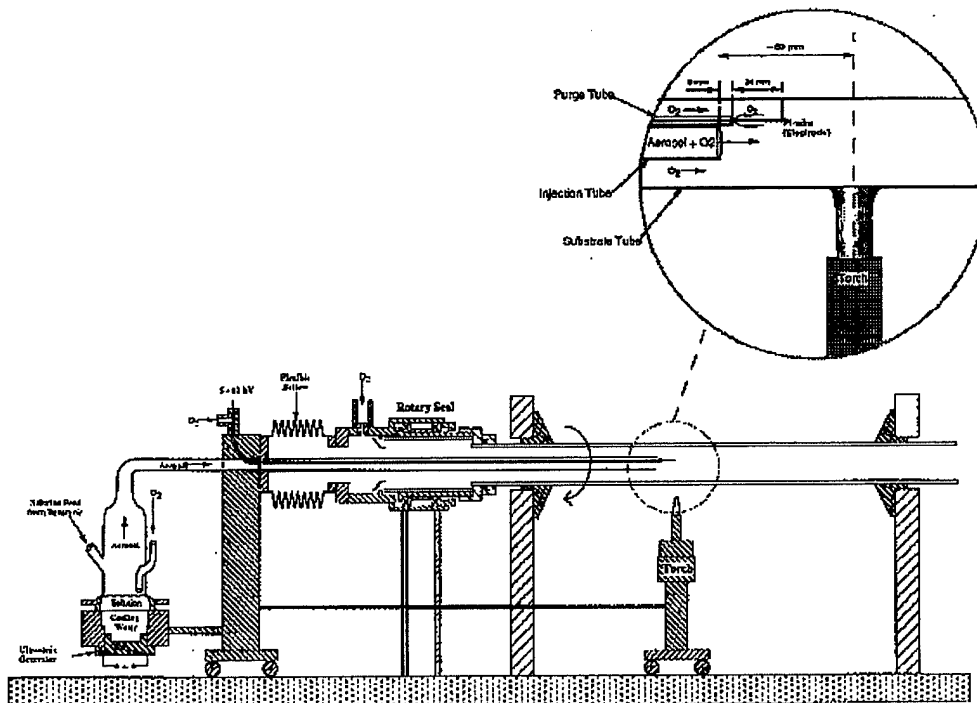


Figure 7. Aerosol Deposition in MCVD

The relative merits of the various techniques for fiber laser fabrication are presented in Table 1. This was the work of J. Simpson while he was at Bell Laboratories. It clearly shows that of all processing techniques, only aerosol deposition combines three out of four advantages when contrasted with other processing methods.

	Intrinsic Loss	Co-Dopant Concentration Control	Re-Dopant Profile Control	Alternate Hosts
MCVD				
Vapor Phase	↑	↓	↑	↓
Solution	↓	↑	↓	↑
Aerosol	↓	↑	↑	↑
Vapor Phase	↑	↓	↓	↓
	↓	↑	↓	↑

Table 1. Comparison of different fiber laser processing techniques

The implementation of this process is shown in Figure 8, where the teflon container mounted on an injection tube on the end of the late is capable, in principle, of replacing a \$400,000 gas cabinet. In Figure 8 is presented the absorption spectrum of a low loss erbium doped fiber.

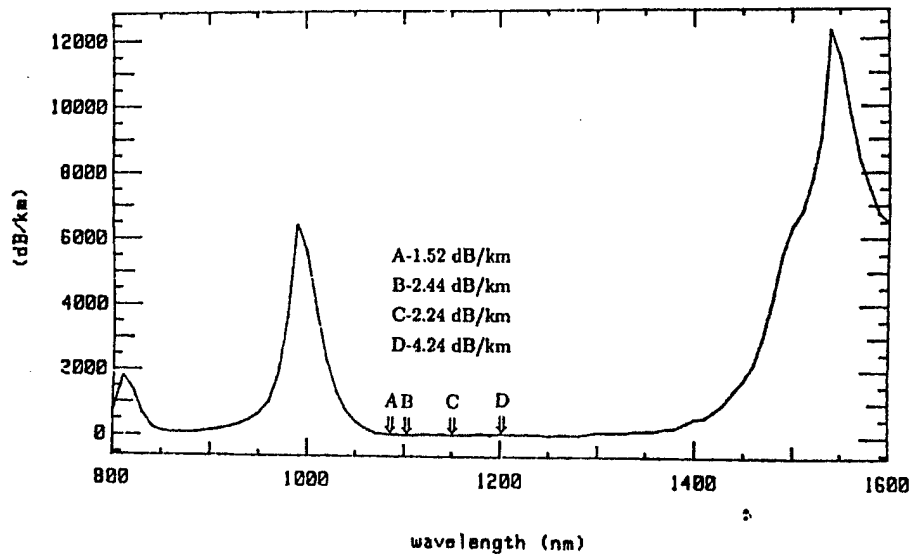


Figure 8. Low loss erbium doped fiber

For high power applications, the most important rare earth doped material is ytterbium. This is a consequence of the simplicity of the spectra and the absence of excited state absorption. Over several hundred Watts of CW radiation have been obtained from Yb double clad fibers, and it is anticipated that this number will increase significantly in the near future with the advent of highly efficient diode sources. In Figure 9 we show the profile of a Yb doped fiber fabricated in our laboratory, and work is in progress on improving the performance of these fibers.

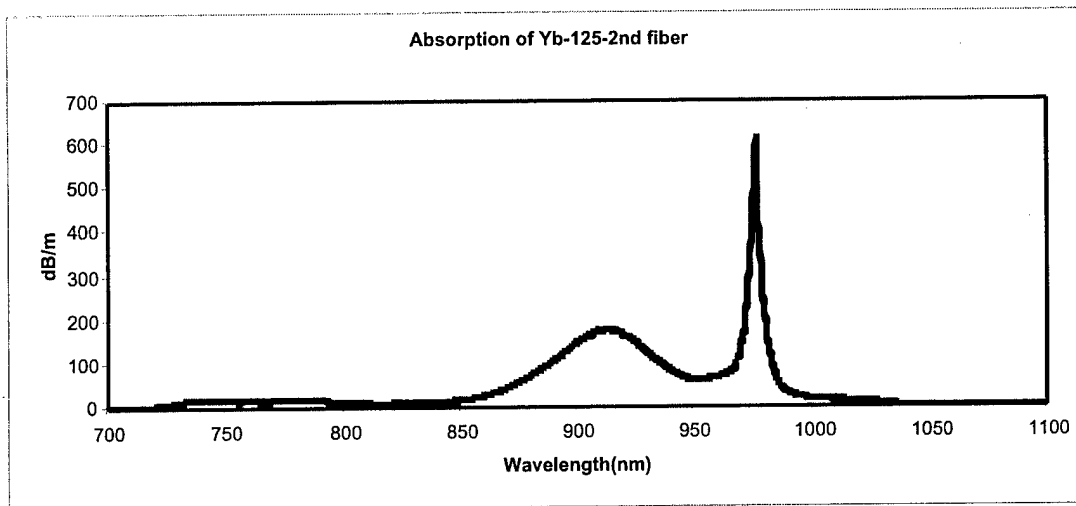


Figure 9. Absorption spectrum of Yb fiber: 56,000 ppm/wt

All-glass double clad fibers were developed to overcome the restrictions of the brightness theorem that prevent low NA, multimode diode radiation from being focused into a single mode core. By designing a multimode structure enclosed in a low index polymer, with a single mode core embedded in the multimode structure, as the diode radiation, focused into the large area of the multimode part of the fiber, travels along the fiber, it causes an inversion. This results in an increase in the brightness of the diode pump radiation by several orders of magnitude. It is possible to achieve single mode output of well over 100 W CW and the material limitations have not yet been reached.

There are several possibilities to couple light into the double clad fiber, either from the side, or from the end. Side coupling usually means taking pig-tailed diodes, stripping the coating, stripping the coating of the double clad fiber (low index), fusing the two so that evanescent wave coupling transfers diode pump energy to the double clad fiber and, ultimately, to the double clad rare earth doped core. End pumping has the advantage of being able to fusion splice fiber coupled diode sources. In addition, there is the possibility of a glass to glass fusion which can not occur with side pumping, which, until now, requires low index polymer coating which, in high power situations, is less durable

A New Laser Design

We have begun some preliminary work on a new concept in a laser cavity. It offers the convenience of end-pumping through fusion splicing of fiber connected diode sources, and it also has the possibility of multiple sources for end pumping in a traveling wave configuration.

This work has just begun in the latter months of this effort, and much remains to be done. In Figure 10 is shown the essence of this concept. We take a Glans-Thompson prism, a polarizing beam splitter. If this is made of yttrium vanadate, it has the following singular characteristics. First, it can withstand energy densities of up to 0.4

MW/cm², and, in addition, the polarization extinction ratio is 1/100,000. On each surface we place a zero order 1/4 wave plate at 45° to the crystal axis. Thus, as indicated in Figure 10, we have a schematic of such a device. The blue is the yttrium

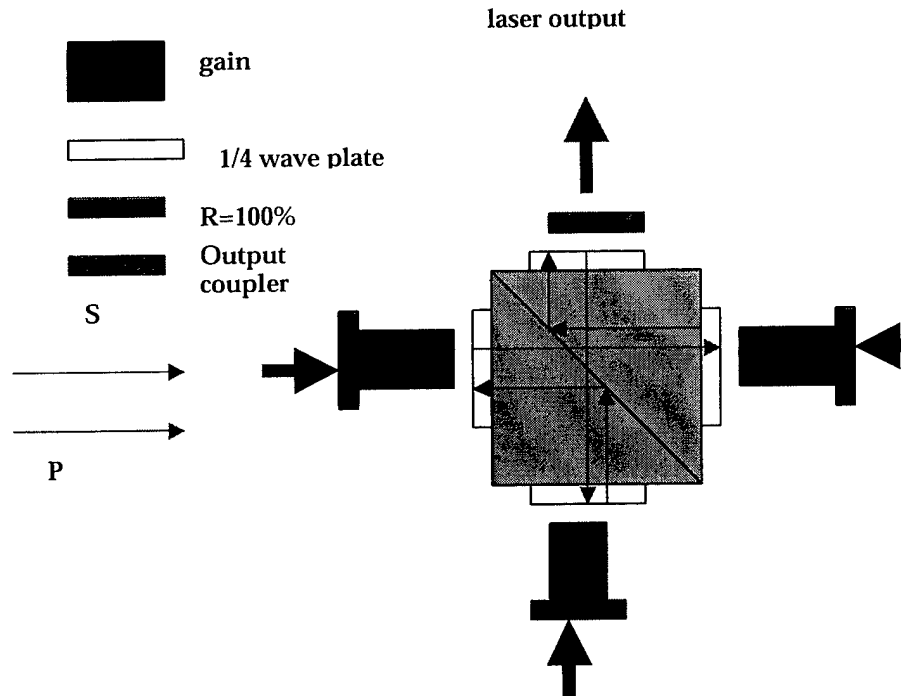


Figure 10. "Multi arm" laser oscillator

vanadate beam splitter. The red sections correspond to gain modules that may be either rod lasers or fiber lasers. They are each associated with a dichroic mirror and a pump source. It is to be stressed that these modules do not form a cavity. Only through their mutual interaction is a cavity formed. In this manner, the difficult problem of combining laser sources is completely avoided, since the gain media interact only in a single cavity.

If we follow radiation emanating from the bottom, it will be, for example, S radiation that will be reflected to the left by the beam splitter. It goes through the 1/4 wave plate on the left, becomes circularly polarized and amplified, is reflected and amplified again to pass a second time through the 1/4 wave plate. This changes the S polarization vector into P polarization. This passes now across the polarizer to pass through the 1/4 wave plate on the right hand side. It becomes amplified, reflected, and amplified again in the second pass through the amplifier before exiting through the 1/4 wave plate on the right and side. It now exits again as S polarization, is reflected to the top, passes again through a 1/4 wave plate, is partially reflected by the output coupler, passes again through the 1/4 wave plate to exit as P polarization that goes to the amplifier section on the bottom.

We plan the construction of such a device in the near future, and we plan to file for a patent on this concept.

In order to be able to make full use of an all-glass structure to be used in conjunction with the proposed device, we are developing a Ta doped preform as shown in Figure 11. Tantalum has the advantage that it has no absorption bands in the IR (if in the right valence state), it can be doped using our above-described aerosol technique, and it has a thermal expansion coefficient much closer to that of silica than germania. Work is still in progress.

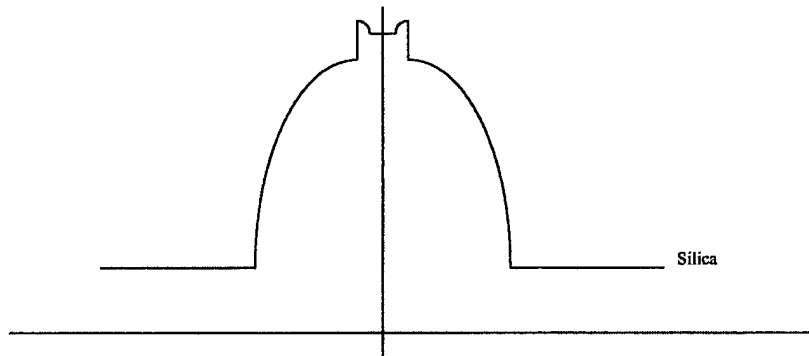


Figure 12. Tantalum doped double clad fiber with rare earth doped core

Polarization Mode Dispersion in Passive devices

In the following, we present a technique that we have developed that is a possibly new method for the measurement of PMD (Polarization Mode Dispersion) in passive devices. Although it will not enable the measurement of PMD in an active system, it is of interest to have this information to characterize passive devices inserted into a telecom system to ascertain how they can impact the overall system behavior.

Any optical anisotropy in a waveguide will result in different components of the electric field vector propagating at different velocities. The detectors used in telecommunications systems are not sensitive to polarization, so if the "fast" part of a pulse emitted later in time catches up with the "slow" part of pulse emitted at an earlier time, signal degradation occurs. This is schematically illustrated in Figure 1.

Schematic of PMD

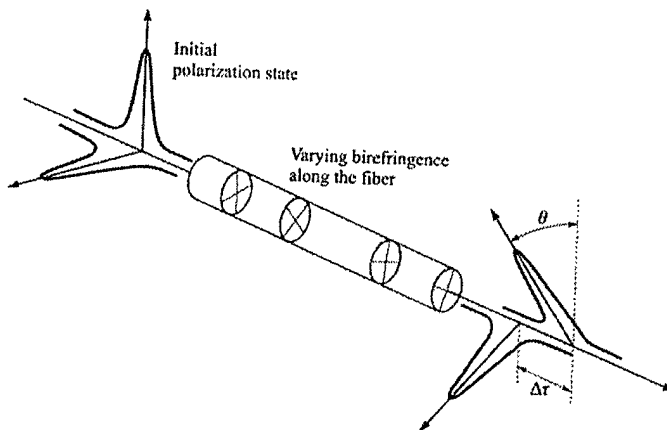


Figure 13. PMD

This is a difficult measurement to make, since the $\Delta\tau$ shown in Figure 13 can be a very small quantity.

We now consider the principles upon which this new type of measurement will be based. The frequency (or wavelength) of a laser will be determined by the cavity length and the index of refraction. Depending upon the cavity length, a series of cavity modes exist whose frequency is given by the following relation, where m is an integer.

$$\nu_m = \frac{C}{2nL} \quad (1)$$

Since m is an integer, the frequency separation of any two neighboring modes will be give as

$$(\nu_m - \nu_{m+1}) \equiv \delta\nu_{xx} = \frac{C}{2nL} \quad (2)$$

If we consider the separation of two modes, with the relation $\nu\lambda = C$, for a cavity length of 1 m and a wavelength of 1.5 microns, $\nu_{xx} = 1$ MHz, and this corresponds to a wavelength separation between longitudinal modes of 7×10^{-3} pm (picometer). This is a quantity that can never be measured optically. However, if we have the lasing output with the longitudinal modes impinge on a RFSA (Radio Frequency Spectrum Analyzer), we can easily distinguish the beating of these modes. This is illustrated in Figure 14.

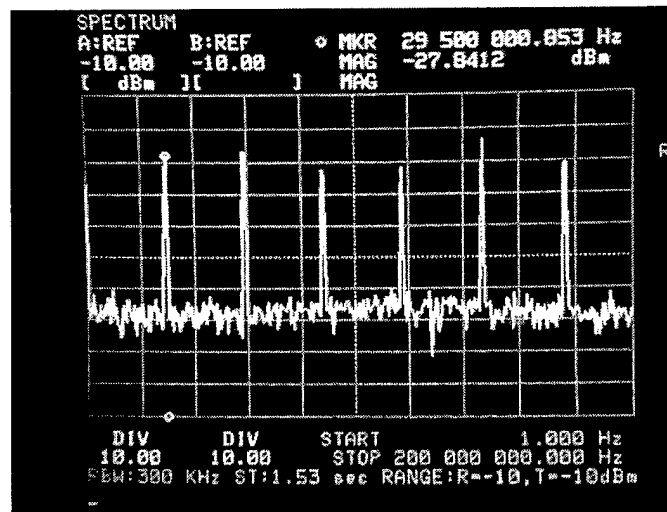


Figure 14. Longitudinal laser mode beating

Thus, it is not possible with an optical experiment to measure the wavelength separation of longitudinal modes, since they are too closely spaced for an optical instrument to resolve. Only the frequency beating can be readily observed. We now consider the situation in which there is a refractive index anisotropy in the laser cavity so that there is an effective refractive

index in the x direction and in the y direction. Z is the axis of the laser, and x and y are arbitrary orientations orthogonal to one another. For this case, there will be two sets of longitudinal modes. This is schematically illustrated in Figure 15.

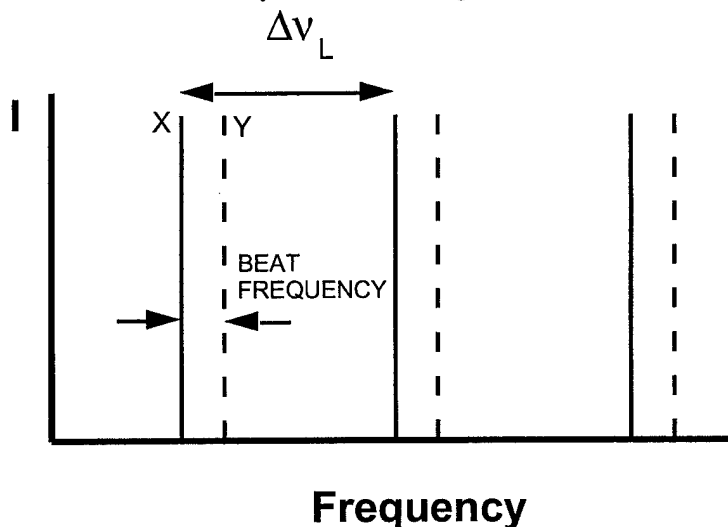
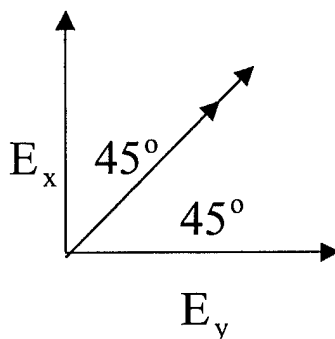


Figure 15. Longitudinal modes, x and y

The presence of these two modes is solely a consequence of their being an optical anisotropy within the laser cavity. If, as noted above, the spacing in wavelength between the x-x longitudinal modes is so small that it can not be measured with optical techniques, then the x-y spacing is even considerably smaller. If we put the output from the laser that has two sets of longitudinal modes onto the detector of a RFS (Radio Frequency Spectrum Analyzer), then, as a consequence of the nearly equal separation of x-x and y-y longitudinal modes, we will observe only a single set of mode beating signals such as has been presented in Figure 2. However, if we put a polarizer at 45 degrees to the x-y axis, then both the x and y components of the field will be projected onto this 45 degree axis. This is schematically



illustrated in Figure 16.

Figure 16. Projection of x and y field components using polarizer

If the output from the laser is put through the polarizer as indicated above, then there will be symmetric beating such that the m th x mode will beat with the m th mode from y, the m th y mode will beat with the $(m+1)$ x mode. Thus, there will be a symmetric beat pattern about the longitudinal modes. This is schematically shown in Figure 17.

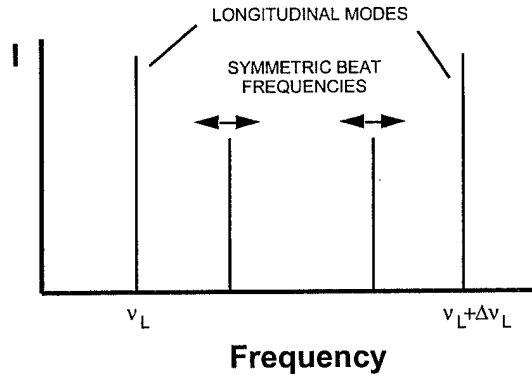


Figure 17. Pattern of symmetric beating of x-y longitudinal modes

In Figure 18, we see the actual beating of the polarization modes of x and y.

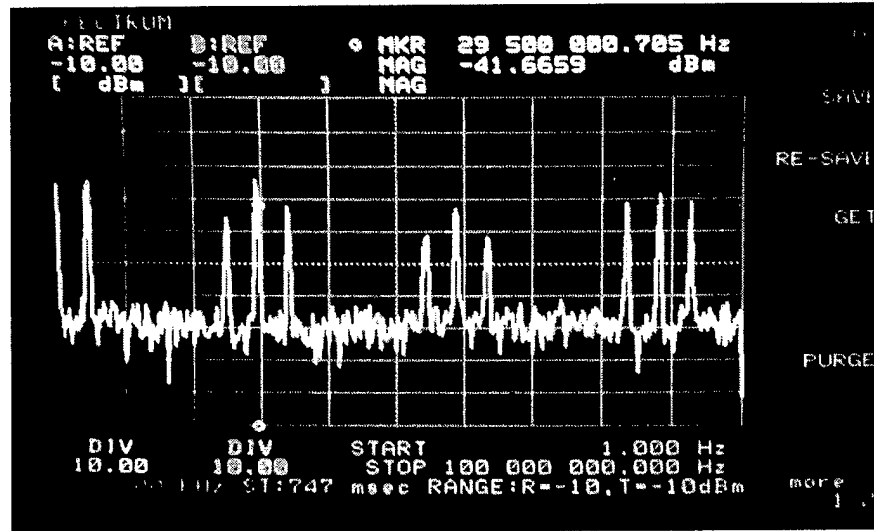


Figure 18. Polarization mode beating

This simple experiment has significant consequences for the measurement of PMD in passive devices. First, however, we write the following expression for the frequency differences between the x and y longitudinal modes.

$$dv_{x-y} = \frac{C}{n_x n_y L} (n_x - n_y) \cong \frac{C}{Ln^2} \delta n_{xy} \quad (3)$$

Where $\delta n_{xy} \equiv n(x) - n(y)$. We also note that $\delta n_{xy} = (C/L)\tau_{\text{PMD}}$. When this is substituted into the above equation, we obtain the following result.

$$\delta v_{x-y} = \frac{C}{Ln^2} \delta n_{xy} = \left[\frac{C}{nL} \right]^2 \tau_{\text{PMD}} \quad (4)$$

It is this result that allows an extremely sensitive measurement of τ_{PMD} , since the quantity $\left[\frac{C}{nL} \right]^2$ can be extremely large. That is, if $L=1\text{m}$, and $n=1.5$, then, for a value of $\delta v_{x-y} = 100\text{Hz}$, we find that $\tau_{\text{PMD}} = 0.25 \times 10^{-18}$ sec. We will now show how this can be used in a measurement of PMD in a passive device.

Consider a laser cavity with a gain medium of length L_1 in which there is no PMD, that is there is no anisotropy in the refractive index. We add onto this an element in which PMD may be present, and the length of this element is L_2 . The mirrors defining the cavity are separated by the sum of the two lengths. In addition, a minute separation is left between the two elements, so that there are two cavities within the mirror. In this case, there will be longitudinal modes characteristic of both of the lengths, and, if the lengths are different, there will be no difficulty in separating the longitudinal modes. This configuration is schematically illustrated in Figure 19.

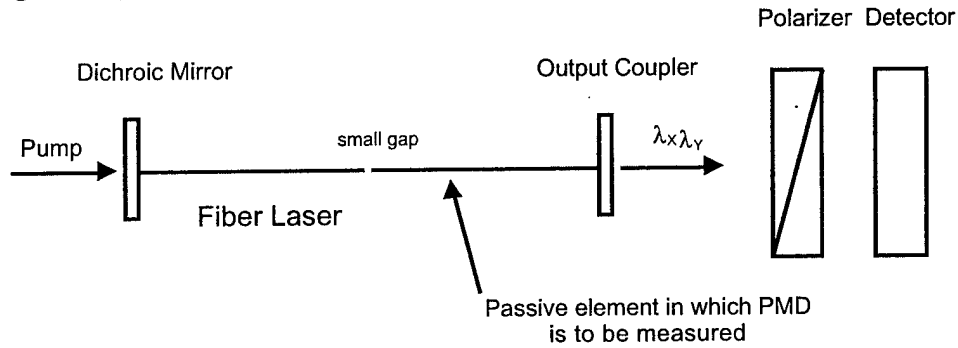


Figure 19. Passive device inserted in laser cavity

An impossible measurement optically, becomes a relatively simple measurement electronically. In Table 1 we present the PMD times that are capable of being obtained for a series of lengths and beat frequencies.

Length-L (m)	measurable beat frequency (Hz) δv_{x-y}	PMD - τ_{PMD} (sec) (shortest)	$\frac{\delta v_{m-(m+1)}}{2}$ (Hz)	τ_{PMD} (sec) limited by 1/2 free spectral range
1	100	2.5×10^{-15}	5×10^7	2.5×10^{-9}
1	1000	25×10^{-15}		
.1	100	25×10^{-18}	5×10^8	2.5×10^{-10}
.1	1000	250×10^{-18}		

Table 1. PMD characteristics

Table 1 is to be interpreted in the following manner. By inserting a passive device in a laser cavity, the minimum PMD measurement that can be determined is a function of the length of the passive element inserted into the cavity and the minimum beat frequency that can be measured. We have chosen two typical values of the limiting beat frequency, 100 and 1000 Hz. 1000 Hz is easily measured, 100 Hz, requires more precise instrumentation. In either case, the PMD times are extremely short. We must also question the dynamic range of such a device. If we examine Figure 8, we observe the beat frequency $\delta\nu_{x-y}$. The longitudinal modes (of either x or y) will be stationary, and we can measure the relative beat frequency relative to this to obtain the PMD time. If we insert passive devices whose PMD times we wish to measure into the cavity, then, as their PMD times increase, the two symmetric modes will approach one another, and, eventually they will pass through one another. Thus, in a simple application, the dynamic range of this measurement technique is 1/2 the free spectral range of the longitudinal mode separation.

In conclusion, we have demonstrated a technique by which the placing of a passive element within a laser cavity, in particular the cavity of a fiber laser, it is possible to measure the beat frequency of two wavelengths associated with the presence of anisotropies in the refractive index. This can be directly related to the PMD time associated with the device. In this manner, extremely precise measurements of PMD may be obtained using a simple technique. An instrument can be readily constructed that will achieve the above described measurement.

Research Accomplishments under AFOSR Support

1. During the past three years we have moved our Laboratory for Lightwave Technology to the Boston University Photonics Center. This laboratory is housed in 3,500 square feet of architect designed space. The components of this facility are a deposition laboratory with two MCVD lathes, and an OVD lathe. The newest MCVD lathe is a state-of-the-art Nextrom system. We have entered into an agreement with Nextrom so that this facility will encompass the latest in fiber fabrication technology. The second component of this laboratory is a new Nextrom optical fiber draw tower, with a partial equipment donation from Lucent Technologies. There is also an optical laboratory for development of fiber based devices, high power fiber lasers, and optical fiber sensors. The final component of this facility is a CVD laboratory for thin film growth. This is the most modern, and best equipped optical fiber laboratory at any US university.

2. Development of an aerosol technique capable of the convective transport of glass oxide precursors of low vapor pressure. We regard this as the best technique for the fabrication of optical fiber lasers. In particular, we emphasize organometallic precursors, with TEOS as the solvent. Within the past two years, the availability of almost any element in organometallic form has increased significantly. Two years ago, it was difficult to dope Si and Ge simultaneously, since the separate ethoxides would precipitate rather than remain in the liquid phase. Now, there are many suitable liquid compounds with a -Ge-Si-configuration. This also allows the possibility of aerosol transport for photosensitive fibers.

3. We have developed a series of optical fiber sensors based upon an ability to measure in situ thin film growth. By using the end of the fiber as a "witness sample",

and by monitoring the back reflected light, we have developed algorithms that permit the monitoring of thickness, refractive index, and a parameter characterizing surface roughness. Since we can monitor the growth, we can also deposit $1/4$ wave stacks at the end of the fiber. Thus, a relatively narrow band (10 nm) Bragg grating is formed at the fiber end. This was done with alternating layers of silicon nitride and silicon rich silicon nitride. The reflectivity can exceed 90%. As this fiber Bragg grating is heated, the peak reflectivity of the grating shifts with temperature, and we have packaged the grating to measure temperatures in excess of 1,000 centigrade. We have also developed a program to use white light in conjunction with an Ocean Optics spectrometer that permits us to multiplex many of these gratings simultaneously. This algorithm is also of use in the monitoring of Bragg gratings at different wavelengths along the fiber, and discussions are in progress to use this technique to monitor mast bending on an America Cup yacht and to measure turbine inlet temperature in a project developed by Siemens.

4. We had previously cited a novel technique for the continuous wavelength tuning of fiber lasers using a 2×2 coupler embedded in a polymer with a large dn/dT . For erbium, a change in temperature of 20 centigrade was sufficient to tune the erbium from 1527 nm to 1573 nm.

5. We have recently developed a method of accurately determining where the wavelength is located in a tunable fiber laser. If we consider a fiber laser with a slight amount of polarization, and of sufficient length that there are several longitudinal modes, then the following technique can be used. With regard to the longitudinal modes, a fiber laser of 10 m will have a longitudinal mode spacing of 1 MHz. If there is any polarization component as a consequence, for example, of an elliptical core, then there will be x and y longitudinal modes, with the frequency separation of the x modes equal to the frequency separation of the y modes. Lasing will occur on two separate, but incredibly closely spaced wavelengths. These can not be resolved with an optical spectrum analyzer. If the laser output with the two wavelengths (x and y) is sent into an RFSP (radio frequency spectrum analyzer), then, since the x and y frequency separation is equal, there will be no differentiation between x and y signals, even though they have different frequencies (wavelengths). However, if a 45° polarizer is placed before the signal goes into the RFSA, then, x and y frequencies (wavelengths) are projected onto the same axis. These two frequencies will beat against one another, and this signal can be easily measured. Thus, an impossible measurement in the optical regime is transferred to a simple measurement in the RF (or lower) regime. A frequency separation of 1 kHz can be easily measured, and this corresponds, at 1.55 microns, to a wavelength separation of approximately 10^{-8} nm. If we tune the laser, then we have observed that the change in the refractive index difference between x and y is periodic. If the number of cycles is counted, and the slope is monitored, then, over the whole gain spectrum of the erbium laser, it is possible to measure wavelength with extreme accuracy, i.e., a fraction of a picometer. Since this is a relative measurement between x and y, a single frequency reference within this gain bandwidth is needed. This work is to be published in Optics Letters.

6. Having noted that the wavelength difference in a fiber laser can be accurately measured by the above described technique, we are able to measure PMD (Polarization Mode Dispersion) in passive optical components with great accuracy. The PMD in a passive device is solely a product of the differences in refractive indices in two orthogonal directions in the device. Manufacturers who fabricate such devices must

know the contribution of PMD that their device introduces within a system. This is a difficult measurement to make; however, it can be done quite simply in the following manner. If the passive device is introduced within the fiber laser cavity, then, if there is any PMD in the device, there will be lasing on both x and y components. This beat frequency can be measured as described above, and subfemtosecond delay times can be measured quite easily. We have made attempts to get a 1 x 16 AWG (arrayed wave guide) to lase within a cavity so that its PMD can be measured, and have achieved partial success. This project is being discussed with Tektronix, who were given the problem of how to make this measurement by Alcatel, and we have proposed this solution. This also allows the possibility of an AWG laser in which the passive device becomes an active laser at the properly spaced ITU telecommunications channels.

7. Fiber laser intra-cavity spectroscopy that has the possibility of compact detection of materials with an absorption signature under the gain bandwidth of the fiber laser. Many atmospheric pollutant gases fall in these categories.

8. Intra-cavity spectroscopy is basically a single beam technique that does not permit ratiometric techniques such as BRD (Balanced Ratiometric Detection) for noise reduction. By using polarization paddles with a polarization beam splitter, it has been possible to construct two independent cavities from the same fiber laser, one with y polarization, and one with x polarization. This permits the placing of an absorber in one arm, and using subtracting the output from the output of the other reference cavity. We believe that it will be possible to combine the inherent sensitivity of intra cavity spectroscopy with a fundamental two beam noise reduction technique.

9. A new type of laser cavity is being developed by which it will be possible to have access to many end pumping ports, and the radiation will travel multiple times through the gain medium. The fact that end pumping is conveniently possible for both high power double clad fiber laser as well as for rod lasers is a distinct advantage. In addition, with rod gain sources, the use of phase conjugate mirrors for maintaining phase quality at high powers is desirable.

Invited talks

1. Autonomous University of Mexico, Department of Materials Science and Engineering: Novel processing of Photonic Materials
2. Dartmouth University, the Jones Lecture, Materials Photonic Processing, novel techniques in PMD measurements.
3. SPIE, Photonics West, Diode Pumped Fiber lasers
4. OFS (formerly Lucent Technologies), Fiber Research at the Photonics Center
5. Nufem Fiber Optics, Specialty Fibers

Publications

1. "Highly Accurate method for Single-Mode Fiber Laser Wavelength Measurement", J. Hernandez-Cordero, V.A. Kozlov, and T. F. Morse, IEEE Photonics Technology Letters, Vol. 14, NO. 1, January 2002
2. V.A. Kozlov, J. Hernandez-Cordero, R.L. Shubochkin, A.L.G. Carter, and T.F. Morse, "Silica-Air Double-Clad Optical Fiber", IEEE Photonics Technology Letters, vol. 12, no. 8, August 2000.
3. Theodore F. Morse, Yifei He, and Fei Luo, "An optical Fiber Sensor for the Measurement of Elevated Temperatures", IEICE Trans. Electron., Vol. E83-C, No. 3, March, 2000, pp. 298-302.

4. J. Hernandez-Cordero, V.A. Kozlov, A.L.G. Carter and T.F. Morse, "Polarization effects in a high-birefringence elliptical fiber laser with a Bragg grating in a low-birefringence fiber". *Applied Optics*, v. 39, No. 6, pp. 972-977, 2000.
5. V.A. Kozlov, J. Hernandez-Cordero, and T.F. Morse, "All fiber coherent beam combining of fiber laser", *Optics Letters*, vol. 24, No. 24, Dec. 15, 1999, pp. 1814-1816.
6. Yifei He, Brian W. Sheldon, and Theodore Morse, "In Situ Fiber Optical Sensor for the Measurement of Thin Films", *IEICE Trans. Electron.*, Vol. E83, No. 3, March, 2000, pp. 315-325.
7. Fei Luo, Jingyuan Liu, Naibing Ma, T.F. Morse, "A fiber optic microbend sensor for distributed sensing application in the structural strain monitoring", *Sensors and Actuators, A*, 75 (1999) 41-44.
8. Kyunghwan Oh, A. Kilian, and T. F. Morse, "A new gas detection technique utilizing amplified spontaneous emission light source from a Tm³⁺/Ho³⁺ co-doped silica fiber in the 2.0 mm region," *Measurement Science and Technology*, Volume 9, Issue 9, pp1409-1412, September 1998.
9. K. Oh and T. F. Morse: "Thermal effects on the excited state absorption and upconversion process of erbium ions in germanosilicate optical fiber", *Journal of Non-Crystalline Solids*, 1999, 259 , pp. 51-56
10. J. Hernandez-Cordero, V.A. Kozlov and T.F. Morse, "Fiber laser polarization tuning using a Hi-Bi fiber Bragg grating", *IEEE Photonics Technology Letters*, 1998, 10, No. 7, pp. 941-943.
11. K. Oh, A. Kilian and T. F. Morse: "Analysis of spectroscopic properties of erbium doped Ta₂O₅- Al₂O₃-SiO₂ optical fiber", *Journal of Non-Crystalline Solids*, 1999, 259 , pp. 10-15
12. R.L. Shubochkin, V.A. Kozlov, A.L.G. Carter and T.F. Morse, "Tunable thulium-doped all-fiber laser", *IEEE Photonics Technology Letters*, 1998, 10, No. 7, p. 944-945.
13. V.A. Kozlov, R.L. Shubochkin, A. Kotze, E. Wetjen, A.L.G. Carter, H. Kung, D.A. Brown and T.F. Morse, "A New Technique for Continuously Tuning of Optical Fiber Lasers", *Applied Optics*, 1998, 37, No. 21, pp. 4897-4901.
14. Kyunghwan Oh, Un-Chul Paek, T.F. Morse, L. Reinhart, Arnd Kilian, "Photoinduced refractive index change in Sm²⁺/Sm³⁺ codoped aluminosilicate fiber by irradiation of an Ar ion laser", *Optics Letters*, Vol. 22, No. 15, 1192 (1997).
15. Kyunghwan Oh, T.F. Morse, L. Reinhart, "Generation of continuous wave oscillation in multiple wavelength from a Tm³⁺ doped Ta₂O₅-Al₂O₃-SiO₂ glass fiber", *SPIE Vol. 2778, Optics for Science and New Technology*, 718 (1996)
16. Kyunghwan Oh, T.F. Morse, L. Reinhart, "Observation of upconversion fluorescence from Ho³⁺ ions assisted by energy transfer and excited state absorption in a Tm³⁺-Ho³⁺ codoped silica fiber" *SPIE Vol. 2778, Optics for Science and New Technology*, 803 (1996)

B. Conference Presentations

During the past three years, under AFOSR support, there have been approximately 10 presentations from the research carried out at the Laboratory for Lightwave Technology. For two of these three years we have presented papers at the High Energy Laser Conference in Albuquerque sponsored by the AFOSR.

Patents under AFOSR Support

A patent has been awarded for "Aerosol Processes for the Manufacture of Planar Waveguides, Inventor(s): KILIAN A,RND HERMAN (US); MACCHESNEY, JOHN BURNETTE (US); MORSE, THEODORE FREDERICK (US)

Applicant(s):: AT & T CORP (US)

Patent number: US5622750

Other patent applications are presently being considered

Below are listed some earlier papers from AFOSR support

1. T.F. Morse, L. Reinhart, A. Kilian, W. Risen, Jr., and W. Cipolla, Jr., "Aerosol Techniques for Glass Formation", *J. Non-Crystalline Solids*, 129 (1991), 93-100.
2. T.F. Morse, et al., "Aerosol Deposition in Modified Chemical Vapor Deposition", *J. Aerosol Sciences*, vol. 22, 1991, pp. 657-666.
3. T.F. Morse, "High Temperature Sol-Gel Processing: Aerosol Techniques in Fiber Fabrication", edited by Lisa Klein, Lower Press, 1994
4. K. Oh, L. Reinhart, Q. Zhang, T.F. Morse, and P. Weber, "Broad-band superfluorescence emission of the ${}^3\text{H}_4 \Rightarrow {}^3\text{H}_6$ transition in a Tm doped multi-component silicate fiber", with , *Optics Letters*, vol. 19, p. 278, 1994.
5. Kyungwhan Oh, T.F. Morse, A. Kilian, L. Reinhart, and P.M. Weber, "Continuous-wave oscillation of thulium sensitized holmium doped silica fiber laser", *Optics Letters*. vol. 19, no. 4, Feb. 15, 1994
6. Kyungwhan Oh, T.F. Morse, L. Reinhart, A. Kilian, and W.M. Risen, Jr., "Spectroscopic analysis of a Eu-doped aluminosilicate optical fiber preform". *J. Non-Crystalline Solids*, 194 (1992) 229-242.
7. Q. Zhang, T. F. Morse, L. Reinhart, A. Kilian, "Temperature Dependence of Effective Cutoff Wavelength in Depressed Clad Single Mode Fibers", *SPIE OE\Fibers*, v. 1792, pp. 1376-145, 1993.
8. Q. Zhang, T.F. Morse, L. Reinhart, and A. Kilian, "New Temperature Sensitive Fiber Sensing Approach", *SPIE, OE/Fibers 92*, Boston, MA, September 1992, *SPIE Proceedings*, v. 1797, pp. 121-131, 1993.
9. S. Wu, J. Strait, R. Fork, and T.F. Morse, "High Power Passively Mode-Locked Er Doped Fiber Laser with a Nonlinear Optical Loop Mirror", *Optics Letters*, 1993, Sept. 1, v18, N17:1444-1446.
10. Q. Zhang, D. Brown, L. Reinhart, and T.F. Morse, "Simple prism based scheme for fabricating Bragg gratings in optical fibers", *Optics Letters*, Dec. 1, 1994.
11. Q. Zhang, D. Brown, L. Reinhart, and T.F. Morse, "Tuning Bragg wavelength by writing gratings on pre-strained fibers", *IEEE Photonics Technology Letters*, Vol. 6, no. 7, September, 1994.
12. Qin Zhang, L. Reinhart, T.F. Morse, and D. Brown, "Linearly and nonlinearly chirped Bragg grating filters fabricated on curved fibers", accepted for publication, *Optics Letters*.
13. T.F. Morse, Mengpang Chen, L. Reinhart, and David A. Brown, "Highly Overcoupled Fused Taper Couplers as Optical Switches" *SPIE publication*, 1994, 15. "The Use of Highly Over-Coupled Couplers to Detect Shifts in Bragg Wavelength", Q. Zhang, D. A. Brown, H. Kung, J. E. Townsend, M. Chen, L.J., Reinhart, and T.F. Morse. accepted for publication,
14. K.S. Kim, T. Tsai, and T.F. Morse, "Exact Closed Form Solutions of Stress Distributions in Polarization Maintaining Fibers", *J. Lightwave Technology*, J.

Lightwave Technology, Jan. 1991.

15. F. Bilodeau, et al., "Ultraviolet-Light Photosensitivity in $r3^+$ -Ge Doped Optical Fiber, Optics Letters, 1990
16. V. Mizrahi, et al., "Direct Test of Model of Efficient Second-Harmonic Generation in Glass Optical Fibers", Appl. Phys. Lett., 53 (7), 15 August 1988.
17. T.F. Morse, L. Reinhart, A. Kilian, W. Risen, Jr., and J.W. Cipolla, Jr., "Aerosol Techniques for Glass Formation", J. Non-Crystalline Solids, 129 (1991), 93-100. T.F. Morse, A. Kilian, L. Reinhart, and J.W. Cipolla, Jr., "Aerosol Deposition in Modified Chemical Vapor Deposition", J. Aerosol Science, vol. 22, 1991, pp. 657-666.
18. T.F. Morse, "Organo-Metallic Aerosol Doping in MCVD: A High Temperature Sol-Gel Process", in Sol-Gel Science and Technology, ed. by Lisa Klein, Kluwer Academic Publishers, 1994.
19. T.F. Morse, K.H. Tsai, K.S. Kim,, "Broad Band Superfluorescent emission of the $^3H_4 \Rightarrow ^3H_6$ transition in a Tm doped multi-component silicate fiber", Optics Letters, March 1994.
20. T.F. Morse, K.H. Tsai, K.S. Kim, "General Solutions for Stress Induced Polarization in Optical Fibers", J. Lightwave Technology, vol. 9, no. 1, P. 7., January 1990. "
21. T.F. Morse, A. Kilian, L. Reinhart, and J.W. Cipolla, Jr., "Aerosol Deposition in Modified Chemical Vapor Deposition". Aerosol Science, vol. 22, 1991, pp. 657-666.", with K.H. Tsai, K.S. Kim, J. Lightwave Technology, vol. 9, no. 1, P. 7., January 1990.
22. Kyunghwan Oh, et al., "Spectroscopic Characteristics of a Eu Doped Aluminosilicate Optical Fiber Preform., Journal of Non-Crystalline Solids, 149 (1992) 229-242. "
23. Kyunghwan Oh, T.F. Morse, L. Reinhart, and A. Kilian "Continuous Wave Oscillation in Tm-Ho Co-doped Silica Fiber", Optics Letters, Vol. 19, No. 4, February 15, 1994
14. Kyunghwan Oh, T.F. Morse, L. Reinhart, "Generation of continuous wave oscillation in multiple wavelength from a Tm+3 doped Ta2O5-Al2O3-SiO2 glass fiber", SPIE Vol. 2778, Optics for Science and New Technology, 718 (1996)
24. Q. Zhang, D.A. Brown, L. Reinhart, and T.F. Morse, "A simple prism scheme for fabricating Bragg gratings in optical fibers", Optics Letters, June, 1994.
25. Zhang, Q., Brown, D.A., L. Reinhart, Morse, T.F., Wang, J.Q., and Xiao, G., "Tuning Bragg Wavelength by Writing Gratings on Prestrained Fibers", Photon. Techno. Lett., Vol. 6, no. 7, p. 839, July 1994.
26. Spectroscopic Analysis of an Eu-doped Aluminosilicate Optical Fiber Preform with Kyunghwan Oh, with T. F. Morse, L. Reinhart and A. Kilian, J. Non-crystalline Solids, 149, 229 (1992).