HIGH RESOLUTION SPECTROSCOPY USING FIBER LASERS*

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ABSTRACT

Fiber lasers show potential for use in high resolution laser spectroscopy. Tunable, single-longitudinal-mode operation has been achieved with free-running laser linewidths of about 1 MHz. It would be straightforward to obtain much narrower linewidths using low frequency electronic feedback. In this paper I review this rapidly changing field and discuss the use of fiber lasers in spectroscopy.

1. Introduction

A fiber laser is a laser in which the active medium is a dopant in the core of an optical fiber. The lasers demonstrated to date use various glass core materials (Ge-silicate, Al-silicate, fluoride, or phosphate glass) doped with rare earth ions such as Nd^{3+} and Er^{3+}. The fibers are pumped longitudinally by another laser of appropriate wavelength, and a cavity can be formed by simply butting mirrors against the ends of the fiber. High pump intensities over large interaction lengths are easily obtained since the pump light is guided in the fiber core, which can be a few micrometers in diameter and meters long. This dramatically reduces the pump power required for lasing; thresholds of a few milliwatts have been achieved in some systems and quantum efficiencies exceeding 90% have been demonstrated. In contrast, the corresponding bulk glass lasers require relatively high pump powers. Fiber lasers are also tunable, usually over more than 50 nm, due to inhomogeneous and homogeneous broadening mechanisms. The disordered nature of the glass host gives rise to nonuniform electric fields which cause Stark splitting and inhomogeneous broadening of the transitions. Homogeneous broadening is caused by nonradiative (phonon) contributions to the transitions. The relative strengths of the homogeneous and inhomogeneous broadening vary with different glass hosts and with temperature, but both are present at significant levels in most fiber lasers.

The first fiber laser was reported in 1963 by Snitzer and Koester,[1] but very little further research was done on this subject until the mid 1980's. Since then, a number of research groups have been working in this area, with a large effort at Southampton University and considerable research at telecommunications companies around the world. A variety of cavity configurations, including Fabry-Perot, Fox-Smith, and ring cavities have been used. Some lasers employ fiber devices such as fiber couplers, loop reflectors, and fiber gratings. Both pulsed (Q switched and mode locked) and cw lasing have been achieved; single-transverse-mode operation is common and single-longitudinal-mode lasers have been demonstrated. In addition, many fiber lasers can be pumped with diode lasers. A good review of this subject and the status of the field as of 1988 can be found in Ref. 2. More recent compilations of papers on fiber lasers and amplifiers are listed in Ref. 3. Table 1 is a list of fiber laser and amplifier wavelengths that have been demonstrated to date. Included in this list are a number of upconversion lasers.

Table 1. Fiber laser and amplifier wavelengths. A dash indicates tunability between wavelengths, (amp) indicates that amplification (but not lasing) has been demonstrated.

DOPANT	LASING λ (nm)	REFERENCE
Neodymium	900 - 945, 1070 - 1135	4
	1052 - 1085	5
	1345, 1350	6
	1360, 1400	7
	1310 - 1370 (amp)	8
Erbium	850	9
	981 - 1004	10
	1510 - 1585	11
	1600, 1660, 1668, 1720	12
	2700	13
Thulium	455, 480, 1510	14
	815 - 825, 1460 - 1510	15
	1650 - 2056	16
	1840 - 1940, 2270 - 2400	15
Holmium	540 - 553, 749 - 754	17
	1380, 2080	18
	2830 - 2950	19
Praseodymium	601 - 618, 631 - 641, 690 - 703, 707 - 725, 880, 886, 902 - 916	20
	888, 1080	21
	1294, 1285 - 1320 (amp)	22
Samarium	650	23
Ytterbium	980	24
	974, 1000 - 1162	21

2. Spectroscopy

To my knowledge, there are only two experiments that have used fiber lasers for spectroscopy: one using a multi-longitudinal-mode Nd^{3+} fiber laser and the other using a single-longitudinal-mode Er^{3+} fiber laser.

2.1. Spectroscopy of a Strontium Ion Using a Nd^{3+} Fiber laser

Researchers at the National Research Council of Canada are working toward an optical frequency standard based on a narrow transition at 674 nm in trapped, laser-cooled Sr^+. In addition to the 422 nm light for laser cooling, another source is needed to depopulate the metastable $4D_{3/2}$ level. Madej and coworkers developed a Nd^{3+} fiber laser[25] and used it to drive the 1092 nm $4D_{3/2} \rightarrow 5P_{1/2}$ transition in a trapped strontium ion.[26] Since the fiber laser was used only for optical pumping (other lasers were used for the precision spectroscopy), narrow linewidth operation was not required.

The fiber laser consisted of a 3 m length of Nd^{3+} doped fiber with a mirror ($R = 99.8\%$ at 1.1 μm) at one end and an external grating, used in Littrow configuration, defining the other end of the cavity. An etalon assembly could be inserted to further restrict the laser bandwidth. The zero order reflection off the grating served as the laser output. The fiber was pumped through the mirror by 0.4 W of 514.5 nm light from an argon ion laser and had an output power of 2 mW at 1092 nm with a linewidth of 10 GHz. The laser could be tuned from 1070 to 1100 nm by tilting the grating. With the etalon assembly installed, the frequency of the laser narrowed to a 300 MHz wide central peak with satellite peaks about 1 GHz away.

2.2 Spectroscopy of Acetylene and Rubidium Using an Er^{3+} Fiber Laser

I am working on producing a wavelength standard in the 1.5 μm region with a linewidth and reproducibility of better than 1 MHz. Such a standard is important for many of the proposed optical communication schemes involving frequency division multiplexing and coherent heterodyne detection. Fiber lasers are attractive candidates for use in wavelength standards because of their potential for narrow linewidth operation. Single-longitudinal-mode Er-doped fiber lasers have been demonstrated previously.[27,28] Using a delayed, self-heterodyne technique, the high frequency contribution (frequencies $\gtrsim 2$ kHz) to the linewidth was measured to be less than 1.4 kHz in Ref. 28.

I have constructed a single-longitudinal-mode erbium-doped fiber laser and have evaluated its frequency noise characteristics.[29] The frequency spectrum of the laser was monitored using a Fabry-Perot (FP) spectrum analyzer which has a transmission peak FWHM of 8 MHz. By observing the transmission through the FP with the laser tuned to the side of a transmission peak, I determined that the short-term frequency fluctuations ($f \geq 5$ Hz) of the laser were less than 1 MHz rms. A spectrum analysis of this noise from 0 to 25 kHz showed no structure beyond 600 Hz. This aspect makes fiber lasers particularly easy to stabilize using an electronic servo.

The Er^{3+} fiber laser is discussed in more detail in Ref. 29. It is a standing-wave laser in a V-shaped folded-cavity configuration. In one arm of the cavity, two short pieces of Er-doped fiber are pumped through a mirror (high reflectance at 1.53 μm) by 528.7 nm light from an Ar^+ laser. A 1200 groove/mm diffraction grating, used in Littrow configuration, is positioned at the end of the other cavity arm. The output is coupled through the folding mirror, which has a transmittance of about 20% at 1.53 μm. The fibers form coupled cavities within the longer cavity, and the overlap of the transmission peaks of these cavities and the bandwidth of the grating selects a single longitudinal mode. Coarse tuning of the wavelength is accomplished by manually tilting the diffraction grating. The fine tuning is done by translating the grating with a piezo-electric transducer (PZT) and stretching one of the fibers with another PZT. The laser is tunable from 1.52 μm to 1.58 μm, and has a threshold of 30 mW (pump power coupled into the fiber) and a peak slope efficiency of 10%.

Atomic and molecular reference lines in the 1.5 μm region are not ideal; atomic transitions are out of excited states, and molecular lines are weak overtone or combination bands. I stabilized my fiber laser to the sides of several lines near 1.53 μm in the $\nu_1 + \nu_3$ vibrational band of acetylene ($^{12}C_2H_2$) by feeding an error signal to the grating-tilt PZT.[29] With a servo bandwidth of a few hundred hertz, the laser's frequency fluctuations were reduced to less than 500 kHz rms. The long term frequency drift was reduced dramatically, but it was difficult to evaluate this quantitatively because of the drift of the FP spectrum analyzer. The FWHM of the acetylene lines was about 550 MHz, primarily due to Doppler broadening. I attempted to perform Doppler-free saturated absorption spectroscopy on these lines, but concluded that this was not practical due to the weakness of the lines.

I have identified rubidium as a promising narrow linewidth atomic reference in the 1.5 μm region. A two step excitation scheme is required: the $5S_{1/2}$ (ground state) $\rightarrow 5P_{3/2}$ transition at 780 nm followed by the $5P_{3/2} \rightarrow 4D_{5/2}$ transition at 1.529 μm. The Rb atom also has a transition near 1.3 μm ($5P_{1/2} \rightarrow 6S_{1/2}$), which is another optical communications region. I have performed the two step excitation by sending 780 nm diode laser light and a counterpropagating beam of 1.529 μm light from the fiber laser through a room temperature cell of ^{87}Rb. The diode laser's frequency was controlled by an external grating which also reduced it's linewidth to less than 1 MHz. In the counterpropagating geometry, the 1.529 μm transition linewidth was nearly Doppler-free since only a narrow velocity distribution of atoms was excited by the diode laser. Figure 1(a) shows the absorption of the fiber laser light due to the $5P_{3/2}(F=3) \rightarrow 4D_{5/2}(F'=3\ \&\ 4)$ transitions. The stronger line ($F=3 \rightarrow F'=4$) has an absorption of 10% and a FWHM of 14 MHz.

To produce a wavelength standard at 1.529 μm, it is necessary to stabilize both the diode laser and fiber laser frequencies to the respective Rb absorption lines. Doppler-free saturated absorption signals were obtained on the 780 nm 5S → 5P transition using the standard technique of observing the absorption of a weak probe beam which is counterpropagating relative to a saturating beam. The diode laser frequency was then modulated at 2 kHz and a derivative of the probe absorption signal was obtained using phase sensitive detection. This error signal was fed back to a PZT which translated the diode laser grating and stabilized the diode laser's frequency to the $5S_{1/2}(F=2) \rightarrow 5P_{3/2}(F=3)$ transition. The 2 kHz modulation of the diode laser frequency also caused an effective modulation of the 1.529 μm 5P → 4D transition frequency since it modulated the atomic velocity selected by the diode laser, thereby modulating the Doppler shift. A derivative error signal for the fiber laser, shown in Fig. 1(b), was obtained using phase sensitive detection of the fiber laser absorption signal at 2 kHz. The fiber laser's frequency was then stabilized to the $5P_{3/2}(F=3) \rightarrow 4D_{5/2}(F'=4)$ transition by sending this error signal to the fiber laser grating PZT. This servoloop had a bandwidth of a few hundred hertz and reduced the short-term frequency fluctuations of the fiber laser to less than 500 kHz rms.

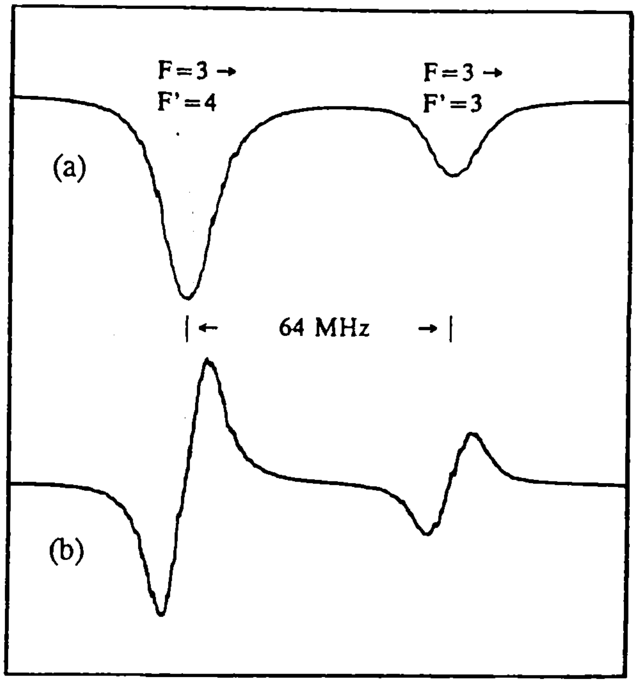

Figure 1 (a) Scan of the $5P_{3/2}(F=3) \rightarrow 4D_{5/2}(F'=3\ \&\ 4)$ transitions in ^{87}Rb near 1.529 μm. The absorption is 10% on the F=3 → F'=4 line. (b) Derivative of (a) obtained using phase sensitive detection.

3. Future

In the wavelength standard work, I need to evaluate the stability of the fiber laser-Rb standard. The best way to do this is to compare two separate systems. I plan to make a second system which will use cold, trapped Rb atoms as a reference. This will eliminate the Doppler broadening and increase the number of atoms that interact with the laser. The fiber laser could be improved by using an internal fiber Bragg grating[30] as the primary wavelength selective element. This would improve the free running stability of the laser, since the laser would be less sensitive to vibration (fewer external elements), and the temperature of the cavity would be easier to control. A fiber grating would also substantially reduce the losses in the cavity and enable diode laser pumping; Er^{3+} can be pumped with 980 nm or 1.48 μm diode lasers, which are now available commercially at moderate (100 mW) powers. It would also be interesting to further investigate the narrow-linewidth capability of fiber lasers by stabilizing them to stable, high finesse cavities using a higher bandwidth servo system.

Fiber lasers can be relatively inexpensive tunable sources for high resolution spectroscopy. This is especially true for the fibers that can be pumped with diode lasers. Future developments in fiber lasers will make them even better sources for spectroscopy. These include: better availability of doped fiber and fiber components (such as fiber gratings), and new lasing wavelengths and components. Fiber lasers also show great promise for use in ultra-high resolution spectroscopy; it may be possible to reduce the linewidth of a fiber laser to a few hertz.

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4. References

1. C.J. Koester and E. Snitzer, *Appl. Opt.* **3** (1963) 1182.
2. P. Urquhart, *IEE Proceedings* **135** Pt. J (1988) 385.
3. *Proc. SPIE "Fiber laser Sources and Amplifiers"* **1171** (1990) and **1373** (1991); *Optical Fibre Lasers and Amplifiers*, ed. P.W. France (Blackie/CRC Press), to be published.
4. I.P. Alcock, A.I. Ferguson, D.C. Hanna, and A.C. Tropper, *Opt. Lett.* **11** (1986) 709.
5. C.A. Millar, I.D. Miller, D.B. Mortimore, B.J. Ainslie, and P. Urquhart, *IEE Proc. Part J* **135** (1988) 303.
6. M.C. Brierley and C.A. Millar, *Electron. Lett.* **24** (1988) 438; M.C. Brierley and M. H. Hunt, *Proc. SPIE* **1171** (1990) 157.
7. F. Hakimi et al., *Opt. Lett.* **14** (1989) 1060.
8. Y. Miyajima, T. Komukai, and T. Sugawa, *Electron. Lett.* **26** (1990) 194; J.E. Pedersen, M.C. Brierley, S.F. Carter, and P.W. France, ibid p. 329.
9. C.A. Millar, M.C. Brierley, M.H. Hunt, and S.F. Carter, *Electron. Lett.* **26** (1990), 1871.
10. J.Y. Allain, M. Monerie, and H. Poignant, *Electron. Lett.* **25** (1989) 1082.
11. R. Wyatt, *Electron. Lett.* **26** (1989) 1498.
12. R.G. Smart, J.N. Carter, D.C. Hanna, and A.C. Tropper, *Electron. Lett.* **26** (1990) 649.
13. J.Y. Allain, M. Monerie, and H. Poignant, *Electron. Lett.* **25** (1989) 28.
14. J.Y. Allain, M. Monerie, and H. Poignant, *Electron. Lett.* **26** (1990) 166.
15. J.Y. Allain, M. Monerie, and H. Poignant, *Electron. Lett.* **25** (1989) 1660.
16. W.L. Barnes, J.E. Townsend, *Electron. Lett.* **26** (1990) 746; D.C. Hanna, R.M. Percival, R.G. Smart, and A.C. Tropper, *Opt. Commun.* **75** (1990) 283.
17. J.Y. Allain, M. Monerie, and H. Poignant, *Electron. Lett.* **26** (1990) 261.
18. M.C. Brierley, P.W. France, and C.A. Millar, *Electron. Lett.* **24** (1988) 539.
19. L. WetenLamp, *Electron. Lett.* **26** (1990) 883.
20. J.Y. Allain, M. Monerie, and H. Poignant, *Electron. Lett.* **27** (1991) 189.
21. P.J. Suni et al., *Proc. SPIE* **1171** (1990) 244.
22. Y. Durteste, M. Monerie, J.Y. Allain, and H. Poignant, *Electron. Lett.* **27** (1991) 627; S.F. Carter, D. Szebesta, S.T. Davey, R. Wyatt, M.C. Brierley, and P.W. France, ibid p.629.
23. M.C. Farries, P.R. Morkel, and J.E. Townsend, *Proc. SPIE* **1171** (1990) 271.
24. J.R. Armitage, R. Wyatt, B.J. Ainslie, and S.P. Craig-Ryan, *Electron. Lett* **25** (1989) 298.
25. A.A. Madej, W.E. Berger, G.R. Hanes, and M.S. O'Sullivan, *Opt. Commun.* **73** (1989) 147.
26. A.A. Madej and J.D. Sankey, *Opt. Lett.* **15** (1990) 634.
27. P. Barnsley, P. Urquhart, C. Millar, and M. Brierley, *J. Opt. Soc. Am. A* **5** (1988) 1339; J.D.C. Jones, P. Urquhart, *Opt. Commun.* **76** (1990) 42; G.J. Cowle, D. N. Payne, and D. Reid, *Electron. Lett.* **27** (1991) 229.
28. K. Iwatsuki, H. Okamura, and M. Saruwatari, *Electron. Lett.* **26** (1990) 2033.
29. S.L. Gilbert, *Opt. Lett.* **16** (1991) 150.
30. G. Meltz, W.W. Morey, and W.H. Glenn, *Opt. Lett.* **14** (1989) 823.