Mode Competition in Raman Fiber Lasers with Two Different Fabry-Perot Cavities

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ABSTRACT

Experimental studies on the mode competition in CW fiber laser pumped Raman fiber lasers with two different F-P cavities are carried out. The first cavity consists of a dichroic mirror and a cleaved fiber end and the second of two dichroic mirrors. Results show that there is drastic competition in the first cavity and much less one in the second because of efficient lasing mode selection of two dichroic mirrors. Reasons for mode competition are analyzed. There are two main kinds of competition in the cavity: one exists between the $440cm^{-1}$ peak and the $490cm^{-1}$ peak in Raman scattering spectrum; and the other is related with long cavity and spatial hole burning. Output characteristic of the laser and probability of different mode wavelengths are also measured.

Keywords: Mode competition, stimulated Raman scattering, fiber laser, F-P cavity

1. INTRODUCTION

In recent years interest in Raman amplifiers has grown significantly because they can amplify signals at any wavelength, particularly signals cannot be done by an EDFA [1-2]. This feature and other advantages make Raman amplifiers attractive for use in optical telecommunications. Raman amplification is based on the stimulated Raman scattering (SRS) effect in which an incident photon is annihilated to form an optical phonon and a longer-wavelength photon under high light intensities. This process is stimulated by incident photons at the longer wavelength so that amplification occurs. Since this is a nonlinear process, high pump powers are required. Generally, there are two approaches to design a pump source for a Raman amplifier [3]. The first, sources are achieved through polarization and wavelength multiplexing of several laser diodes, as the optical power of the commercially available pump diodes is limited within 200~300mW [4]. The second, which is a more practical way, is to use the Raman process itself to frequency-shift from a high-power fiber laser [5]. This may be accomplished using an Yb-doped double clad fiber laser to pump a cascaded Raman fiber laser [6]. Thus, it is of essential importance to study Raman fiber lasers and their stability at operating wavelength and output power. Such fiber lasers often use Fabry-Perot cavity as a resonant cavity, which is simple and practical, but multi-mode competition is easily occurred in it, which is disadvantageous to the stability. Researches on mechanisms resulting mode competition in a Raman fiber laser are helpful to circumvent the problem. In this paper, experimental studies on mode competition with two different F-P cavities were carried out in Raman fiber lasers based on standard Corning SMF-28TM silica fiber.

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2. METHODOLOGY

Raman is a nonlinear optical process in which intense pump light couples to vibrational modes of the glass and is reradiated at a longer wavelength [7]. This process can amplify a signal if the pump is at an appropriately shorter wavelength than the signal. The Raman gain spectrum of conventional silica fibers has maximum gain at a frequency 13 THz lower than the pump frequency [8] and gain coefficient scales inversely with the pump wavelength. Since the gain spectrum is determined simply by the pump wavelength rather than the fixed energy levels of a dopant, gain can be created at any wavelength with a suitable pump. When intense pump light from a fiber laser is injected into a length of germano-silicate fiber surrounded by sets of highly reflective Bragg gratings, the cascaded Raman converter is formed. The light is contained within the fiber by highly reflective Bragg gratings at each end. Intense light in turn generates Raman gain at the first-order Stokes, the second-order Stokes, and so forth. That is, cascaded Raman generation can be understood as an iteration of fundamental stimulated Raman scattering (SRS) processes in which each generated Stokes wave acts as a pump to produce the next one.

Figure 1 shows the experimental setup. The basic resonant cavity consists of a dichroic mirror (M_1) and another resonant mirror as which the cleaved fiber end is used in the first cavity and another dichroic mirror (M_2) in the second cavity. The 1064 nm pump source has its stability <4% and nearly diffraction-limited fundamental transverse beam with M^2 of 1.1. The pump light, with 5 W maximum output power, was launched into the 25-km-long Corning fiber via the mirror M_1 after coupling. The dichroic mirror M_1 has a high transmissivity of >90% at 1064nm and a high reflectivity of >95% at 1117nm. Because the pump wavelength and the laser wavelength are so close that it is difficult for coating to have a high reflectivity at the laser wavelength. The dichroic mirror M_2 has high reflectivity of >99% both at 1064nm and at 1117nm. The transmission spectra of M_1 and M_2 are shown in Fig.2 (a) and (b), respectively. The characteristics of output power and spectrum of the fiber laser were measured with an optical power meter (FIELDMASTER COHERENT) and an OSA (ADVANTEST Q8384 OPTICAL SPECTRUM ANALYZER, minimum resolution 0.01nm, operation wavelength range: 0.6-1.7μm), respectively.

3. RESULTS

3.1 Experiment One

In this part the cavity consists of the dichroic mirror M_1 and the cleaved fiber end. The measured spectrum is quite complex, as shown in Fig.3, including the residual pump wave, the first-order Strokes wave and other higher-order Strokes waves. It is so narrow for the first-order Strokes wave that can be considered as laser oscillation in the cavity, but mode competition is quite drastic. There are two main reasons for mode competition: one exists between the 440cm^{-1} Strokes shift peak and the 490cm^{-1} Strokes shift peak in Raman gain spectrum, which is unique for a Raman fiber laser and often neglected in other papers. As shown in Fig.4 we have typical spectra centered at 1117nm and 1123nm at the same pump power but scanned at different time, respectively, corresponding to Strokes frequency shift of 440cm^{-1} and 490cm^{-1}. The other reason is related with long cavity and spatial hole burning, for example, even 1117 nm wave is predominant, there still exists mode competition in the neighborhood, as shown in Fig.4 (a). Fig.4 (b) describes multi mode competition when 1123 nm wave is predominant. Furthermore, we found the possibility of different modes at different pump power is also different. For the first-order Strokes laser, we used the OSA to randomly scan 100 times and each time noted the center wavelength, then plot a graph with wavelength as abscissa and possibility as Y-coordinate, as described in Fig.5. It is obviously shown that the possibility of 1117nm is higher at lower pump power, while 1123nm higher at larger pump power. This is coincident with previous conclusion that 1117nm wave emerges first because the 440cm^{-1} Strokes shift peak is slightly more than the 490cm^{-1} Strokes shift peak, then increases gradually along with increasing pump power and becomes saturate, at last transfer its energy to 1123nm wave [9]. So 1117 nm wave becomes weak and 1123 nm wave strong, that is, there exists energy red shift from 1117 nm wave to 1123 nm wave within the same order Stokes spectrum. For other higher-order Strokes waves, no laser is formed in the cavity, but with the mirror M_1 which has high reflectivity within the range 1120 to 1500 nm the cavity becomes double pass, so it is easier to observe higher-order Strokes waves than the case without the mirror, by comparing Fig.3 with Fig.6.

3.2 Experiment Two

In this part the cavity consists of two dichroic mirrors M_1 and M_2. The measured spectrum becomes relatively simple, only including the first-order Strokes wave; residual pump wave and higher-order Stokes waves are not observed, as shown in Fig.7. This is because higher transmissivity known from Fig.2 for higher-order Strokes waves makes their threshold too high to form laser oscillations. Though there still exists mode hop, as shown in Fig.8 at the same pump power but scanned at different time, the scope becomes narrower, for example, from 10.42 nm in Fig. 5(b) in Section 3.1 to 7.05 nm in Fig. 9 at the same pump power, by measuring the probability of different mode wavelengths. This is predictable because the selection ability of M_2 is much stronger than it of the cleaved fiber end. Output power are also measured, data of which verse the pump power fall in a straight line, as described in Figure 10. As the mirror has high reflectivity for laser, intensity exists within the cavity, thus output power is much lower. The output light is TEM_{00} by a CCD camera.

4. CONCLUSIONS

Researches on mode competition for the first-order Strokes with two different F-P cavities were performed in detail. The first cavity consists of a dichroic mirror (M_1) (high transmissivity for pump light and high reflectivity for the laser light) and the cleaved fiber end, which is used as the output end, and the second of two dichroic mirrors (the end mirror (M_2) with high reflectivity for both the pump and laser light). Because the mirror M_1 has large bandwidth of high reflectivity including several-order Strokes, and the cleaved fiber end is also a large bandwidth reflector, there is lack of effective mode-selective mechanism in the former cavity, so spectra are pretty complex including residual pump light, the first-order Stokes and higher-order Stokes. On the one hand, there exists mode competition between the 440cm^{-1} Strokes shift peak and the 490cm^{-1} Strokes shift peak in Raman gain spectrum. On the other hand, because of long cavity length and spatial hole burning, multi-mode oscillations are easily formed. In the latter cavity, spectra becomes relatively simple, only includes the first-order Strokes wave. Residual pump light and higher-order Stokes are not observed. Though there still exists mode hop, the scope becomes narrower, for example, from 10.42 nm in the former cavity to 7.05 nm in the second at the same pump power, by measuring the probability of different mode wavelengths. Results show there is drastic competition in the first cavity and much less drastic competition in the second because of efficient lasing mode selection by two dichroic mirrors. It is also convinced that homemade mirrors are feasible for Raman lasers. Further improvement could be achieved by use of Bragg gratings to eliminate mode competition and realize all-fiber and narrow bandwidth Raman fiber laser.

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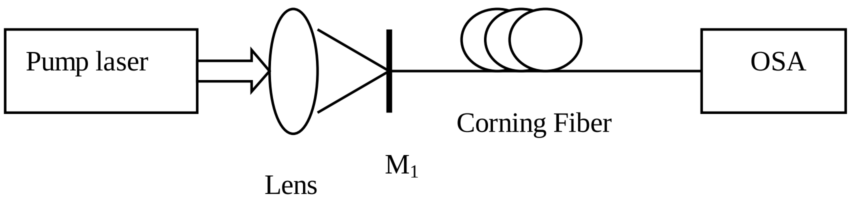


Fig. 1 Schematic configuration of the experimental setup

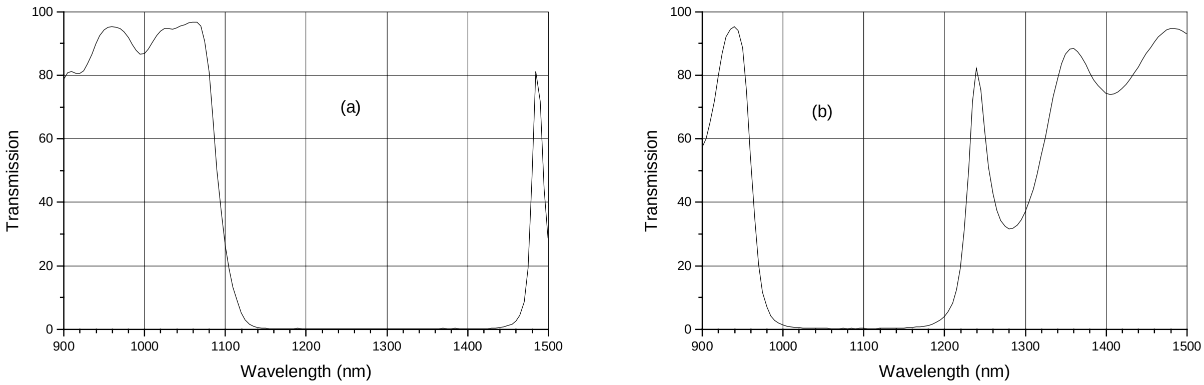


Fig.2 Transmission spectra of mirror (a) M_1 and (b) M_2

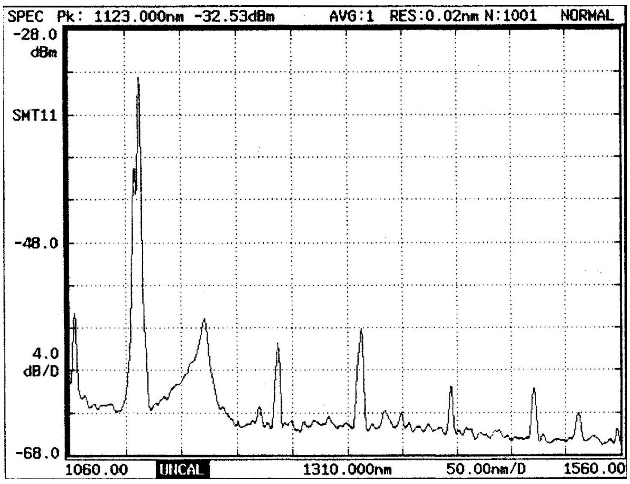


Fig.3 The spectrum of multi-order Strokes wave

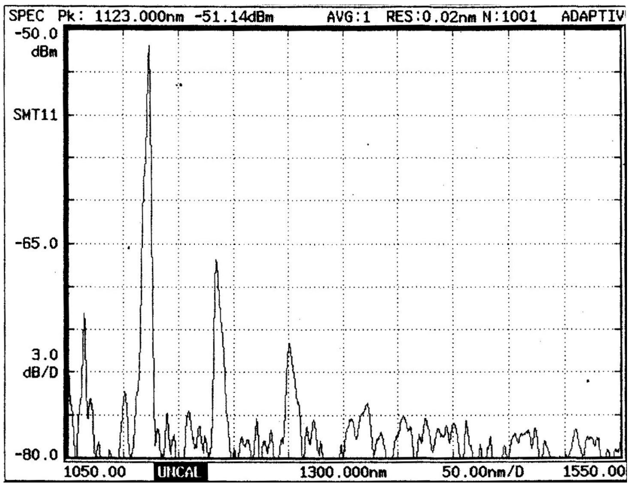


Fig.6 The spectrum of multi-order Strokes wave without M_1

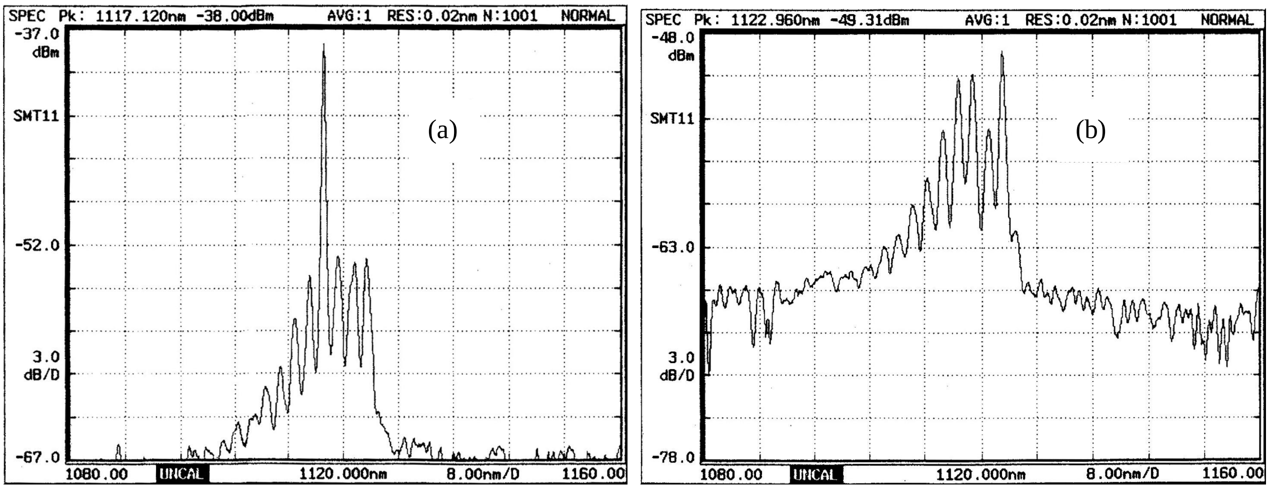


Fig.4 Mode competition for the first-order Raman laser centered at (a)1117 nm (b) 1123nm

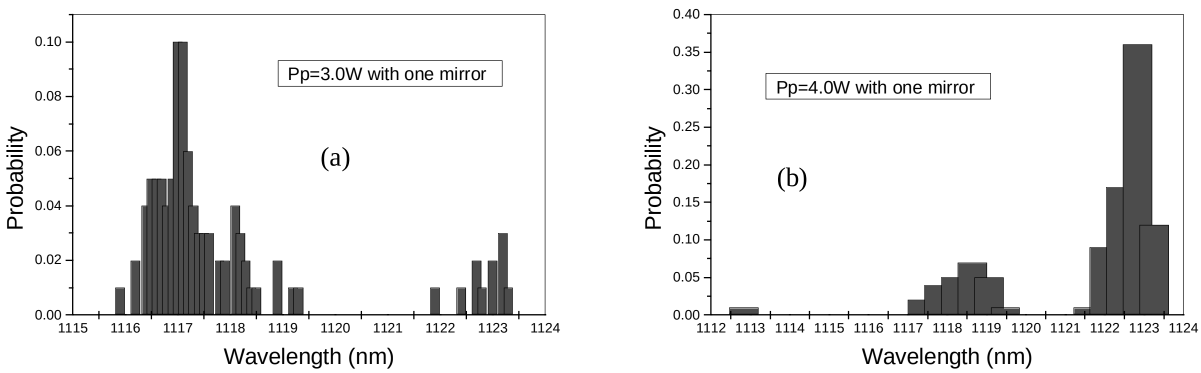


Fig.5 The probability of different modes at different pump power of (a)3.0W (b) 4.0W

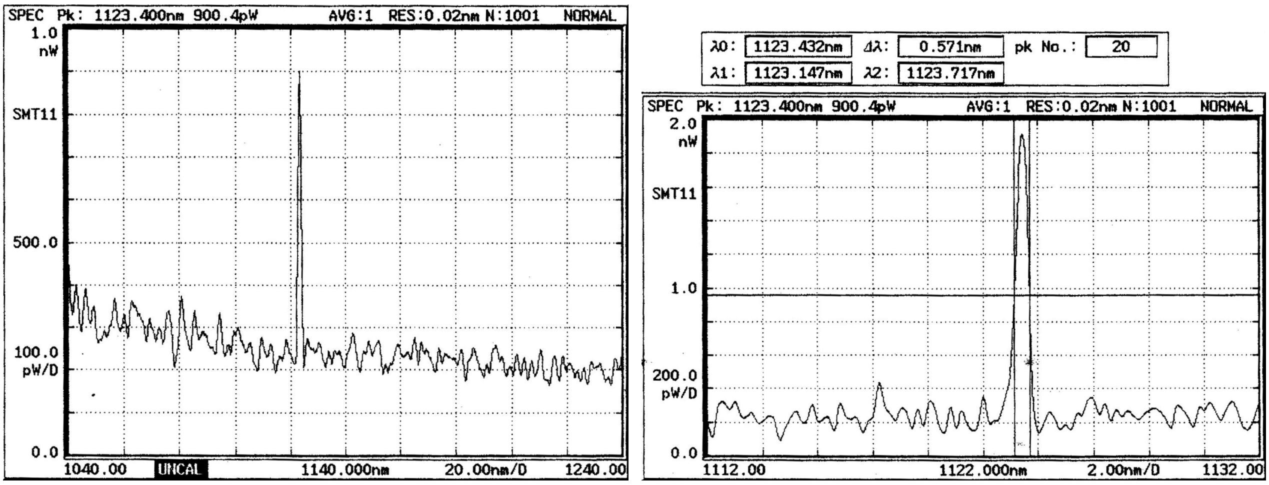


Fig.7 The spectra of the first-order Raman laser with two mirrors (FWHM is measured in the right)

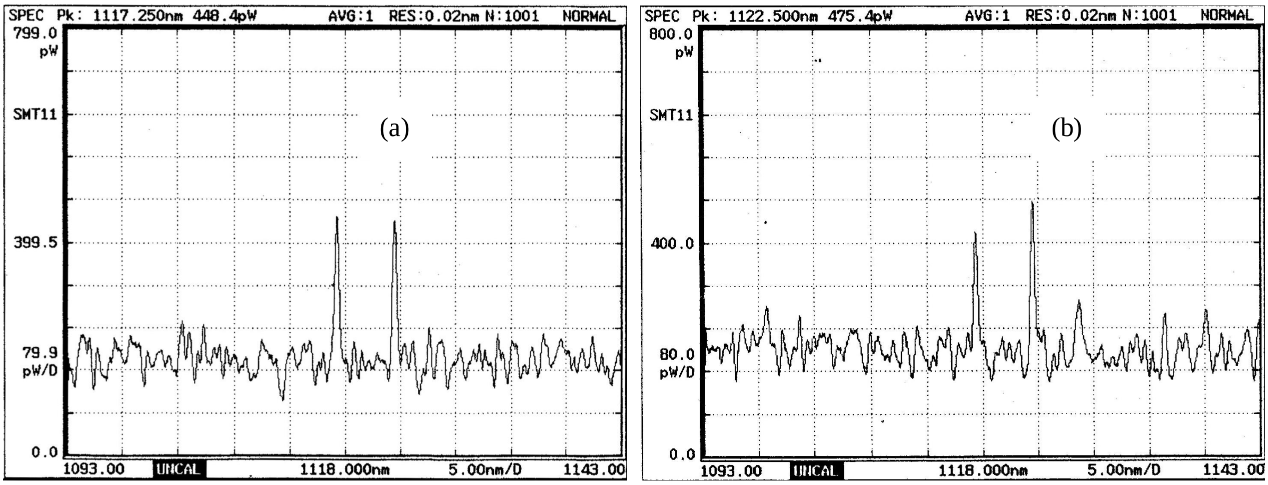
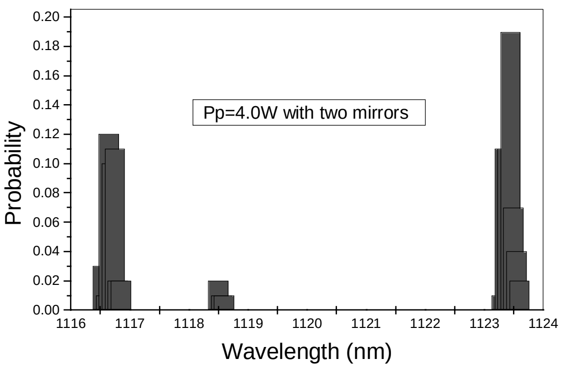


Fig.8 Mode competition for the first-order Raman laser with two mirrors centered at (a) 1117 nm (b) 1123nm



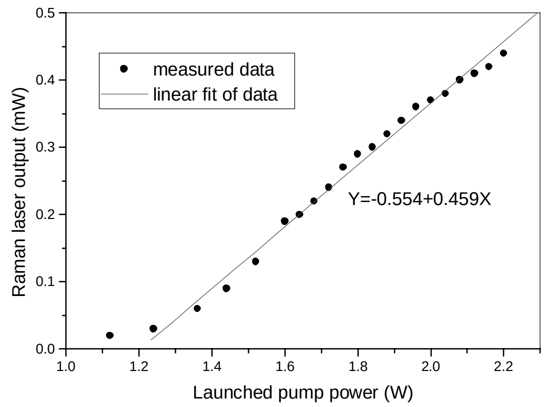


Fig.9 The probability of different mode wavelengths

Fig.10 The graph of laser output verse launched pump power