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High-Power, Efficient, Diode-Pumped Fiber Lasers For Air Force Applications

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13. ABSTRACT (Maximum 200 words)

The UNM portion of this program focused on two areas, namely:
1) Efficient, wavelength-switchable fiber lasers for Air Force applications
2) The development of mid-IR sources, namely 3 μm fiber lasers for pumping longer wavelength sources for IRCM applications.
More specifically, we developed and/or demonstrated:

1. A precisely and rapidly wavelength-switchable 1.5 μm fiber laser source with switching times of ~18 μs
2. A widely tunable wavelength-selectable fiber laser for 8 channels using an FBG string for channel pinning with output powers of each channel of ~12 dBm (16 mW)
3. A broadly tunable wavelength-selectable source using a fiber Sagnac loop filter, with over 25 wavelength-switchable channel outputs with precise 50 GHz channel spacing, excellent output power uniformities of ±0.8 dB over the whole tuning range, and very large (65 dB) side mode suppression ratios
4. A single-mode tunable wavelength selectable fiber laser operating at 8 uniquely selectable wavelength-channels with individual linewidths of <300 kHz in each channel
5. That the optimal pump wavelength for "the 800 nm pump band" pumping of high-power 3 μm mid-IR fiber laser is 799±1 nm (as opposed to earlier reports implying an optimal pump wavelength of 791nm)
6. Optimal designs for custom double-clad Er:ZBLAN fibers for power scaling of such mid-IR lasers to average powers of >10 Watts
7. Compact diode-pumped Q-switched (both actively and passively) mid-IR fiber lasers.

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High-Power, Efficient, Diode-Pumped Fiber Lasers for Air Force Applications

Final Technical Report
For
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"High-Power, Efficient, Diode-Pumped Fiber Lasers for Air Force Applications"

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1) Efficient, wavelength-switchable fiber lasers for Air Force applications
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6. Optimal designs for custom double-clad Er:ZBLAN fibers for power scaling of such mid-IR lasers to average powers of >10 Watts
7. Compact diode-pumped Q-switched (both actively and passively) mid-IR fiber lasers.

I. Er:Silica 1.5 μm novel wavelength-switchable fiber lasers

A. Precisely and rapidly wavelength switchable 1.5 μm fiber laser source

We first focused on the design and demonstration of a narrow-linewidth fiber laser that was switchable (at μs speeds) to just two precise predesignated wavelengths in a manner that it is extendable to a large number of wavelengths. Our approach consisted of the use of two filters such that one filter (composed of a set of fiber Bragg gratings, FBGs) generates a wavelength comb, and a second tunable filter (a fiber Fabry-Perot, FFP-TF) selects the desired wavelength channel [1, 5, 14, 16]. This general scheme for switchable fiber lasers can be implemented using linear, ring or multiple cavity configurations. The configuration chosen for our first experiment is depicted in Fig. 1.

The two fiber Bragg gratings used had peak reflectivities of ~ 30 dB and 3 dB linewidths of ~ 0.4 nm at center wavelengths of 1551.68 nm (λ_1) and 1554.10 nm (λ_2). The FFP filter (Micron Optics) had a linewidth of 0.4 nm and a free spectral range of 40 nm, corresponding to a finesse of ~ 1000. Isolators were placed inside the loop to ensure unidirectional operation and to prevent feedback from wavelengths reflected off the bandstop regions of the FFP transmission spectrum. The output spectra were measured using an Ando AQ-6315A optical spectrum analyzer which has a resolution of 0.05 nm.

The speed of switching was measured by using a tunable bandpass filter and an isolator in front of a 1 GHz InGaAs photodetector. The bandpass filter (Santec OTF-610, 3dB BW = 0.3 nm) was tuned to one channel or the other, to give a 30 dB rejection ratio between the two channels. Rapid switching between the two wavelengths was accomplished with the use of a 1 kHz square wave source (~ 60 ns rise time) to drive the tunable FFP. Fig. 2 depicts spectral data for two different settings of the voltage applied to the PZT element of the FFP. Clear switching between wavelengths corresponding to the peaks of the FBGs was easily observed. The 1551.76 nm (λ_1) signal was selected for V_{FFP} = 33.6 V +/- 0.01 V, while the emission wavelength switched to 1554.17 nm (λ_2) when the FFP voltage was = 34.1 V +/- 0.01 V. About 0.16 nm of fine-tuning, which corresponded to ~30 mV changes in the tunable filter voltage (V_{FFP}), was observed around the center wavelengths λ_1 (1551.76 nm) and λ_2 (1554.17 nm).

The switching time for switching between λ_1 and λ_2 (Fig. 3) was measured to be ~ 25 μs (determined by the use of higher temporal resolution scales). For these experiments, the capacitive loading at the FFP PZT inputs limited the FFP driver's scan speed to several tenths of a ms (typical manufacturer's specification) for an entire FSR (~ 40 nm in our case). As such, the switching time between the two wavelengths (separated by 2.41 nm) is estimated to be ~ 18 μs.

B. Widely tunable (8 nm, Δf=0.8nm) wavelength-selectable fiber laser using an FBG string

We demonstrated a widely tunable (8 nm, Δf = 0.8nm, OSNR > 60 dB) fiber laser based on the use of FBGs for selecting wavelengths, by employing a design where the FBG string entails proper sequencing order of FBG wavelengths [17]. The schematic of the fiber laser design is shown in Fig. 4a. When the FBG string sequence was in the right order, the output power uniformity was observed to be ~0.6 dB, as seen in Fig. 4b. Also, the OSNRs improved to ~60 dB. The output powers for each channel was ~12 dBm (16 mW).

C. Broadly tunable wavelength-selectable source using a fiber Sagnac loop filter

A wavelength-selectable fiber laser using an all-fiber multi-wavelength grid filter (Fig. 5a) was constructed [3, 15, 16]. The laser design is based on a Sagnac birefringence loop filter architecture. The filter has an ~1.6 dB insertion loss, 14 dB peak-to-valley transmission ratios, and can be temperature tuned (Fig. 6) to a very precise match with the ITU-WDM grid. Even though this was demonstrated for telecom applications, the precise temperature tuning of wavelength will enable tuning such a laser precisely to the absorption lines of species of interest. We successfully demonstrated (Fig. 5b) 25 channel outputs with precise 50 GHz channel spacings, excellent output power uniformities of +/- 0.8 dB over the whole tuning range, and very large (65 dB) side mode suppression ratios.

D. Wavelength selectable fiber laser using tunable FBG
Using a tunable FBG in combination with a Fabry-Perot grid filter (either a 1 mm etalon with 100 GHz free spectral range, or a fixed fiber Fabry-Perot filter with a 20 GHz free spectral range), we demonstrated two distinct wavelength-agile sources with channel spacings of 100 GHz and 20 GHz. The fiber laser consists of a ring cavity coupled to a standing wave arm via a 3-port circulator, as depicted schematically in Fig. 7. The recorded data is shown in Figs. 8 and 9.

E. Single-mode tunable wavelength selectable fiber laser
We designed and constructed a novel single-frequency wavelength-selectable source based on a tunable Bragg grating connected to an Er:SiO_2 saturable absorber *line-narrowing filter*. The fiber laser consists of a "hybrid" sigma-shaped cavity with a ring cavity coupled to a standing wave arm via a 3-port circulator, as depicted schematically in Fig. 10. A glass etalon (2 mm thick, 50GHz FSR, 10dB transmission peak-to-valley ratios) was inserted in the ring cavity to act as a wavelength-periodic transmission filter.

A key feature of the linear arm is that the counter-propagating waves of sufficient intensity (40 kW/cm^2) inside the saturable absorber set up a standing wave with preferentially low-loss at a narrow spectral band centered at the peak wavelength of the FBG. In combination with a low-finesse (~7) 50 GHz FSR intracavity glass etalon, the linewidth narrowing effect was significant enough to enable singlemoded outputs at 8 uniquely selected wavelength-channels, as shown in Fig. 12. As the laser longitudinal mode spacings were estimated to be ~3 MHz, we confirmed singlemoded emission via both scanning Fabry-Perot experiments (20 MHz resolution) and self-heterodyne measurements (300 kHz resolution) of the laser output (Fig. 11).

II. <u>High power mid-IR fiber lasers</u>

Goal: Research and development of high-power diode pumped mid-IR lasers based on Er-ZBLAN double-clad fibers.

A. Optimize the efficiency of Er:ZBLAN fiber laser
Output powers of the order of 1W were obtained by pumping double-clad erbium-doped ZBLAN fibers at 791 nm so far. The reported slope efficiencies were 17% (when a highly reflecting mirror was butt coupled against the distal end of the fiber) and 13% (with 4% Fresnel reflections on both ends). 791 nm was assumed to be the optimum pump wavelength for these experiments (which is true for single clad fibers where core pumping is used). However in double clad fibers, the use of an inner cladding for the pump radiation reduces the pump density and hence the excited state absorption (ESA) from the lower laser level. We demonstrated that the optimum pump wavelength is different for double-clad fibers as elucidated below.

A.1. Optimization of the pump wavelength in the 800 nm band for high power mid-IR fiber lasers based on Er-doped double-clad fibers
The pump wavelength was optimized in 800 nm pump band for the attainment of high slope efficiencies. Detailed studies were performed using both double-clad and single-

clad fibers and demonstrated that the slope efficiency increases from 13% to 17% (4% Fresnel reflections from both ends) when the Er-ZBLAN double-clad fiber was pumped at the optimized 799 nm pump wavelength.

A 10W all-wavelength Ar^+ laser was used to pump the Ti:sapphire laser and an output power of ~2.0 W was obtained in the 800 nm band. For a rectangular double-clad fiber with 20,000 ppm Er and 5,000 ppm Pr in ZBLAN, the largest mid-IR signal were observed at a wavelength of 799 nm pump and was independent of the pump intensity (Fig 13). The lasing threshold was 310 mW for 96% output coupler for this optimum pump wavelength (Fig 14).

A.2. Optimization of the pump wavelength in the 980 nm band for high power mid-IR fiber lasers based on Er-doped double-clad fibers

Even though we have optimized the pump wavelength in 800 nm pump band and have obtained higher efficiencies (17% Fresnel reflections at both ends), because of the smaller Stokes shift, the efficiency can be further increased when the Er:ZBLAN doped fiber is pumped in the 980 nm pump band. As such, we also performed detailed studies to optimize the pump wavelength using double-clad and single-clad fibers and demonstrated a slope efficiency of 21% (4% Fresnel reflections from both ends) with respect to the launched powers at the 976 nm pump wavelength.

Custom-designed double-clad fibers with core diameters of 13 µm, an NA = 0.16, and of ion concentrations 20,000 ppm Er and 5,000 ppm Pr in the core were used for these studies. The largest mid-IR output powers were observed at a pump wavelength of 973 nm and this optimum pump wavelength was found to be somewhat independent of the pump intensity (Fig 15). The lasing threshold was 140 mW for 96% output coupler with the use of a near-optimum pump wavelength of 976 nm (Fig 16).

B. Design of custom fiber for high power mid-IR fiber lasers

In order to take advantage of cross relaxation at high concentrations of Er, as has been demonstrated by our group, high doping density Er:ZBLAN double-clad fiber geometries were designed to obtain powers >10W. The design parameters of double-clad Er-doped ZBLAN fibers included a laser core NA of 0.16 (+/- 0.02) and a pump core NA of 0.55 (+/- 0.05). The core should be 15µm (+/- 3 µm) and scattering loss for the core and pump core should be <0.05 dB/m and the core dopant is erbium, at a concentration of 50,000 ppm.

These double clad geometries will enable us to use inexpensive high power diode arrays, such as 19-emitter or 49-emitter diode bars with total output powers of ~35 W at ~976 nm. The alignment of a novel beam shaping technique is in process to couple the high power pump into the active fiber with a coupling efficiency of >75%.

Fiber Geometries (size +/- 10%):

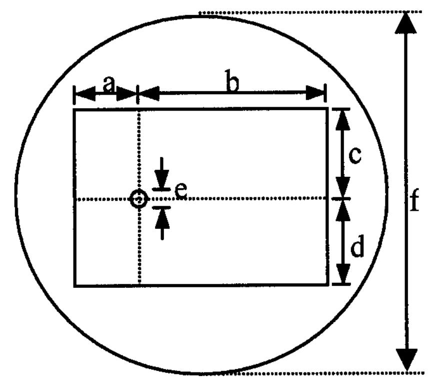
1. a = 50 μm
   b = 150 μm
   c = 75 μm
   d = 75 μm
   e = 15 μm
   f = optimum

2. a = 100 μm
   b = 100 μm
   c = 75 μm
   d = 75 μm
   e = 15 μm
   f = optimum

3. a = 130 μm
   b = 170 μm
   c = 85 μm
   d = 85 μm
   e = 15 μm
   f = optimum

4. a = 150 μm
   b = 150 μm
   c = 85 μm
   d = 85 μm
   e = 15 μm
   f = optimum

Fiber end view showing offset core for number 1 and 3. Fiber geometries 2 and 4 have centered core.



C. Compact diode-pumped passively Q-switched mid-IR fiber lasers

We have demonstrated passive Q-switching (7 μs pulsewidth, 35 kHz rep rate) of mid-IR rare-earth doped fiber lasers by using a liquid gallium mirror as a saturable absorber [7, 8, 13]. A schematic of the experimental set-up is depicted in Fig. 17. It consists of a simple Fabry-Perot cavity defined by the 4% Fresnel reflection off the pump end of the fiber, and a rear mirror defined by a gallium:fluoride glass interface. The gallium was held in a ~3 mm diameter dimple machined into an aluminum block thermally contacted (using silicone paste) onto a thermoelectric cooler. The 20,000 ppm Er:ZBLAN (Thorlabs/KDD) double-clad fiber (L = 20m) was pumped with a high power 790 nm diode array from Optopower. The pulsewidths and pulse shapes were measured with a fast (0.3 ns rise time) InAs photodetector.

When the Peltier cooler was set to temperatures ranging from 10 to 25 °C, Q-switching was observed as depicted in Fig. 18a. Unstable pulsing or CW lasing was observed outside the above-mentioned temperature range. For the data shown in Fig. 13a, the launched pump power was 720 mW and the Ga mirror was set to a temperature of 12.7°C. At these settings, the observed pulsewidth was 7 μs at a rep rate of 37 kHz. As is consistent with the behavior of passively Q-switched fiber lasers, the laser's repetition rate increased with pump power (Fig. 18b), while the pulsewidth had an inverse relation with the pump intensity.

D. Actively Q-switched diode-pumped pulsed mid-IR fiber laser

We designed and constructed an actively Q-switched mid-IR fiber laser using an intracavity acousto-optic modulator (AOM) for the Q-switching. The schematic experimental setup is shown in Fig. 19. The AOM was made of Ge and had an aperture of 2 mm with an ~85% switching efficiency between the zero and first order. The distal end of the fiber was angle-cleaved and collimated using a sapphire AR coated ball lens.

The dependence of the peak powers and pulsewidths on the repetition rate and on AOM pump powers were studied, as depicted in Fig. 20. A pulse energy of 800 nJ was obtained when the pump power was ~2W; the corresponding pump repetition period was 80.4 μs, the peak powers was 590 mW and the 3 dB pulsewidth was 1.35 μs. The dependence of the peak power and pulsewidth on the pump power were also studied, as shown in Fig. 21.

Publications and Patents

Journal Publications

1. N.J.C. Libatique and R.K. Jain, *Precisely and Rapidly Wavelength-Switchable Narrow-Linewidth 1.5-mu m Laser Source for WDM Applications,* IEEE Photon. Techn. Lett., v. 11(#12) pp. 1584-1586 (Dec. 1999).
2. N.J.C. Libatique, J. Tafoya, N.K. Viswanathan, R.K. Jain, and A. Cable, *A "Field-Usable" Diode-Pumped ~120nm Wavelength-Tunable CW Mid-IR Fiber Laser,* Electron. Lett. v. 36(#9) pp. 791-792 (Apr. 2000).
3. N.J.C. Libatique and R.K. Jain, *A Broadly Tunable Wavelength-Selectable WDM Source Using a Fiber Sagnac Loop Filter,* IEEE Photon. Techn. Lett., v. 13(#12), (Dec 2001).

Presentations:

4. N.J.C Libatique and R.K. Jain, *Novel Wavelength-Modulatable and Continuously Tunable Narrow Linewidth Fiber Lasers for Trace Gas Spectroscopy*, Conf. on Lasers and Electro-Optics (CLEO), Paper CThT6 (May 1999)
5. N.C. Libatique and R.K. Jain, *Precisely and Rapidly Wavelength-Switchable Narrow-Linewidth 1.5 μm Laser Source for Wavelength Division Multiplexing Applications*, European Conf. on Optical Communications (ECOC), Nice, France, Paper P1.9 (Sep. 1999)
6. N.J.C Libatique and R.K. Jain, *New Narrow-Linewidth Wavelength-Tunable and Switchable 1.5 micron Laser Source for WDM and Spectroscopic Applications*, OSA Annual Meeting, Paper TuH3 (1999)
7. N.J.C Libatique and R.K. Jain, *A Compact Diode-Pumped Passively Q-Switched Mid-IR Fiber Laser*, Advanced Solid State Lasers, OSA Topical Mtg., Davos Switzerland, Paper MD2-1 (Feb 2000); N.J.C. Libatique, J. Tafoya, S. Feng, D. Mirell, and R.K. Jain, *A Compact Diode-Pumped Passively Q-Switched Mid-IR Fiber Laser*, H.Injeyan, U. Keller, and C. Marshall Eds., Trends in Optics and Photonics (Advanced Solid State Lasers), TOPS v. 34, pp. 417-419 (2000).
8. N.J.C Libatique and R.K. Jain, *A Compact Diode-Pumped Passively Q-Switched Mid-Infrared Fiber Laser*, Conference on Lasers and Electro-Optics (CLEO), Session CMP (May 2000)
9. N.J.C Libatique and R.K. Jain, *A "Field-Usable" Diode-Pumped ~120 nm Wavelength-Tunable CW Mid-Infrared Fiber Laser*, Opt. Soc. of Am. (OSA), Conference on Lasers and Electro-Optics (CLEO), Session CThV (May 2000)
10. N.J.C. Libatique and R.K. Jain, *Large Channel Count Wavelength-Switchable 1.5 μm Lasers for Optical Communications,* CLEO-Europe Postdeadline Paper, CPD2.8, Nice, France (Sep 10-15, 2000)
11. N.J.C. Libatique and R.K. Jain, *Wavelength-Switchable Large Channel Count (~60) 1.5 um Sources for Wavelength Division Multiplexing Applications,* OSA (Optical Society of America) Annual Mtg., Providence, Rhode Island (Oct 22-26, 2000)
12. N.J.C. Libatique and R.K. Jain, *Large Channel Count (~60) Wavelength-Selectable 1.5 um Laser for 50 GHz WDM Applications,* Paper WA5, LEOS (Laser and Electro-Optics Society) 2000 Annual Mtg., Puerto Rico (13-16 Nov)

13. N. J. C. Libatique, B. Srinivasan, and R. K. Jain, *Diode-Pumped Mid-Infrared Fiber Lasers and Applications,* Invited Talk, 3rd Annual Directed Energy Symposium, Kirtland Air Force Base, Albuquerque, New Mexico (Nov. 1 2000)
14. N.J.C. Libatique and R.K. Jain, *Tunable Infrared Fiber Lasers,* Invited Talk, Photonics 2000, Calcutta, India (Dec 2000)
15. N.J.C. Libatique and R.K. Jain, *A Broadly Tunable Wavelength-Selectable WDM Source Using a Fiber Sagnac Loop Filter*, OSA Topical Meeting on Optical Amplifiers and Applications, Stressa, Italy, (July 2001)
16. N.J.C. Libatique and R.K. Jain, Paper MK5, *Large Channel Count Wavelength-Selectable 1.5 um Fiber Lasers for Optical Communications,* OSA Annual Meeting, Long Beach, CA, USA (Oct 15, 2001)
17. N.J.C. Libatique and R.K. Jain, Paper ThK3, *Scalable Multi-Channel Wavelength-Selectable 1.5 μm WDM Source Based on FBG Strings,* OSA Annual Meeting, Long Beach, CA, USA (Oct 18, 2001)

Patents:

1. N.J.C.Libatique and R.K.Jain, Precisely Wavelength-Tunable and Wavelength-Switchable Narrow Linewidth Lasers, UNM reference number, UNM-517.PCT, UNME-0026-1 PCT, US Patent Application filed on 11/24/99, #09/448,869.

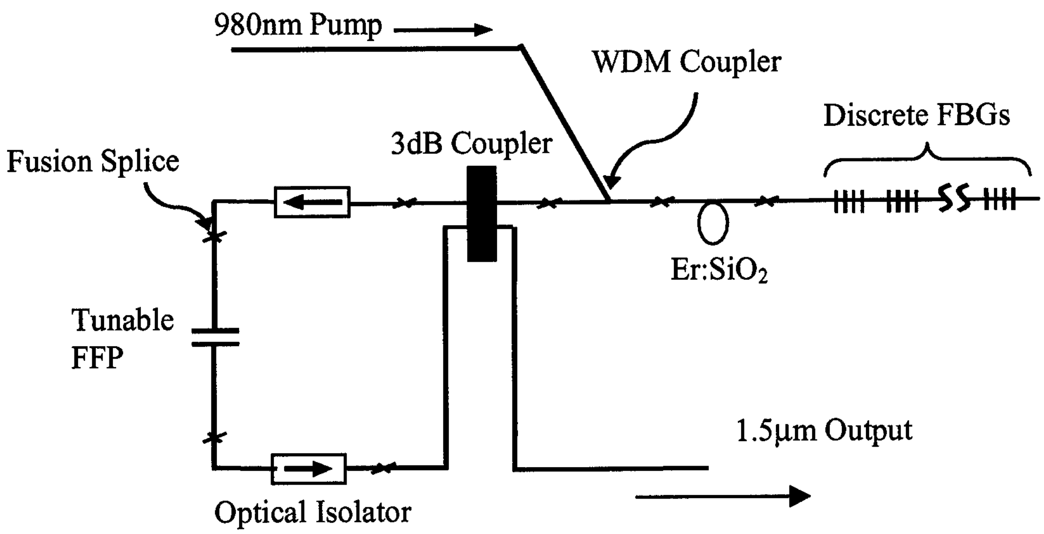
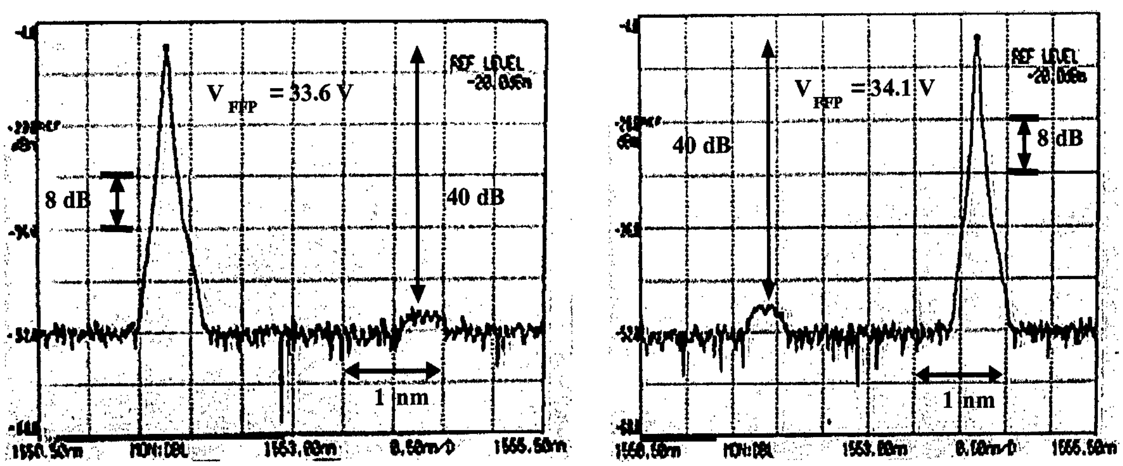


Fig. 1: Schematic experimental setup of a multi-wavelength-switchable laser using a tunable filter (FFP) and several discrete FBGs (each corresponding to a desired "switching" wavelength).



(a) (b)

Fig. 2. Optical spectrum analyzer traces for (a) V_{FFP} = 33.6 V, and (b) V_{FFP} = 34.1 V. Both wavelength scans range from 1550.50 nm to 1555.50nm, and the vertical scale is 8.0 dB/div.

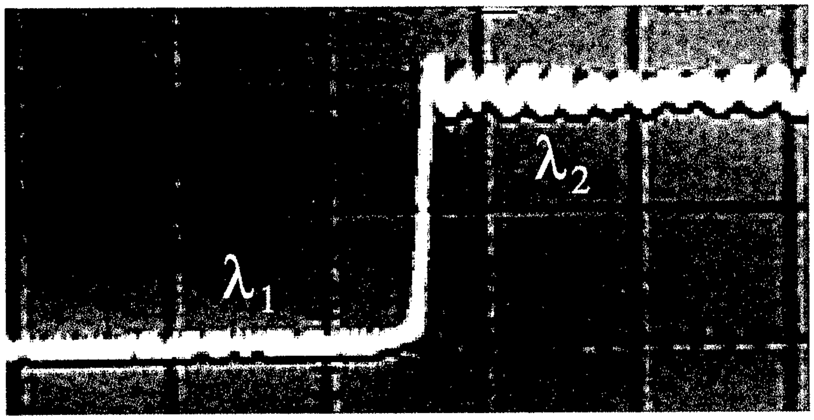


Fig. 3. Photodetector output as laser switches from λ_1 to λ_2. A filter has been inserted before the detector to pass λ_2 and reject λ_1 (30 dB relative attenuation). The horizontal scale is 0.1 ms/div.

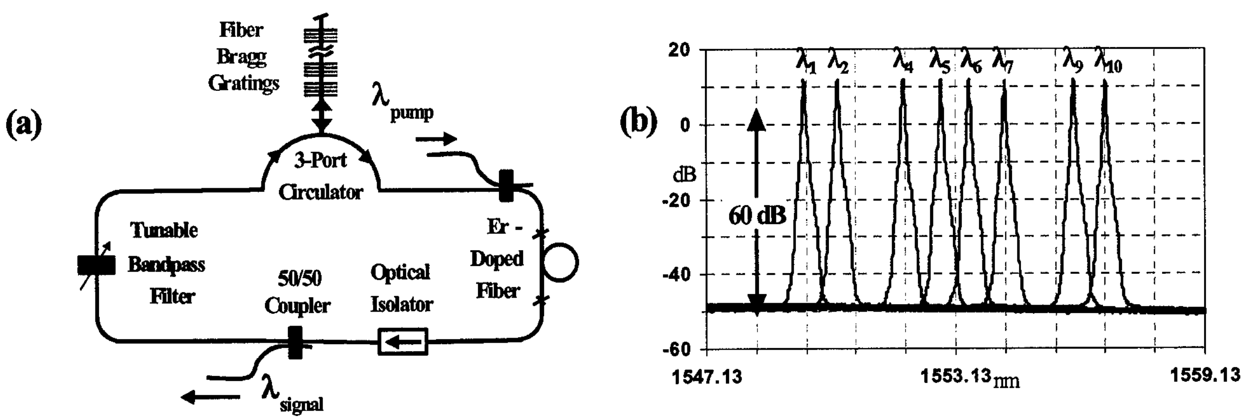


Fig. 4 (a) Schematic of the λ-selectable WDM source based on a string of FBGs
(b) P vs. λ at 8 uniquely selected channels w/ P = 11.99 dBm ± 0.3 dBm.

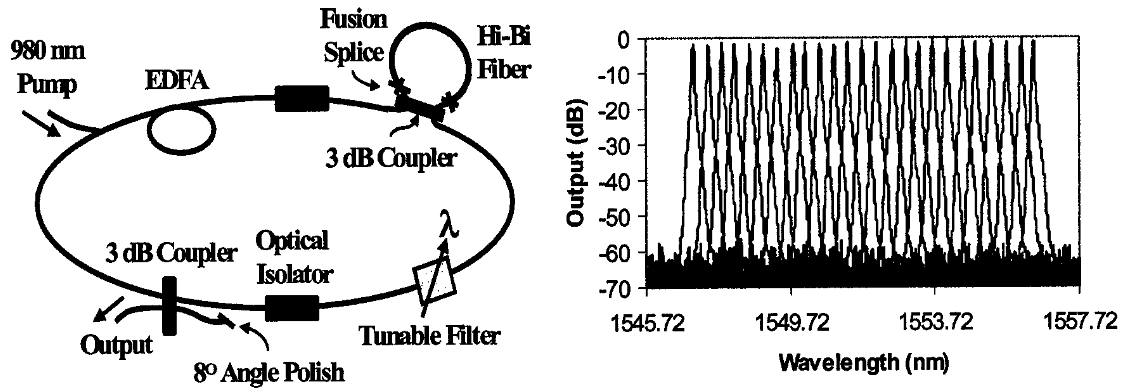


Fig. 5: (a) Fiber laser schematic
(b) Laser output spectra at uniquely selectable wavelength channels.

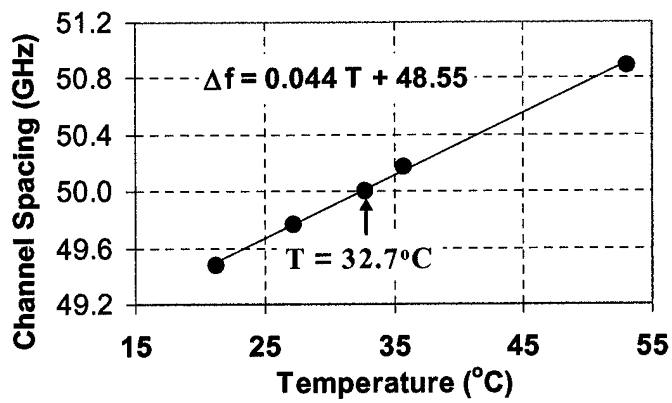


Fig. 6. Temperature tuning of the Sagnac fiber loop filter to a channel spacing to 50.0 GHz (at T=32.7°C).

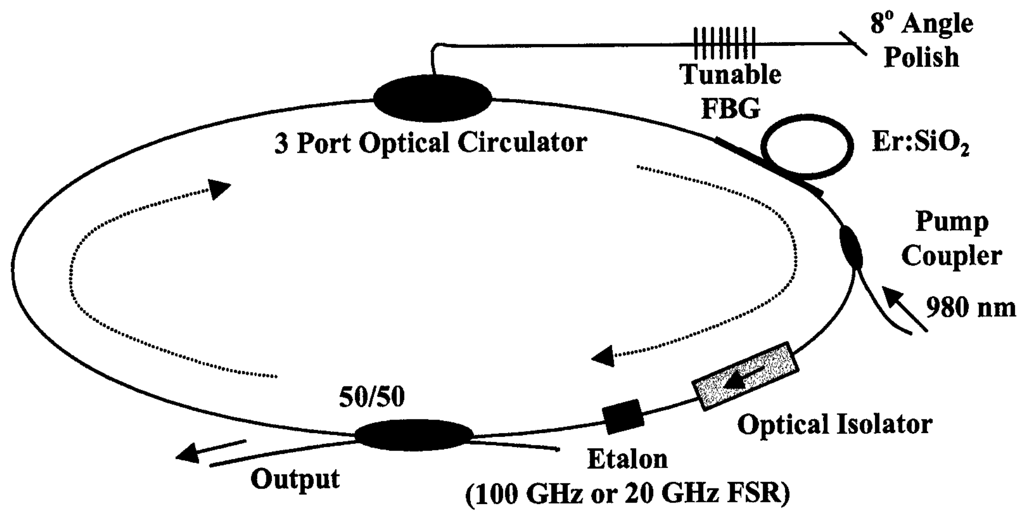


Fig. 7: Schematic of the laser design that was used for demonstrating a wavelength-switchable fiber laser using a tunable FBG and an etalon grid filter.

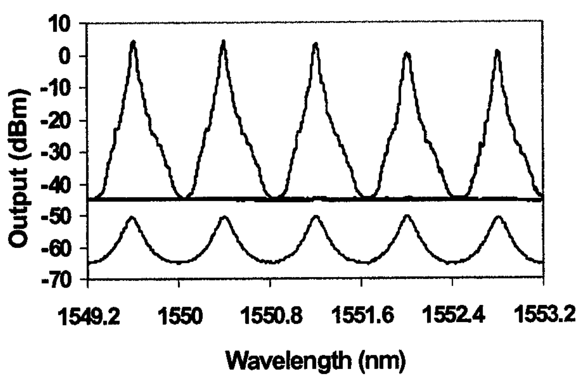


Fig. 8: Top curve (in blue): 5-channel spectral output of λ-agile source with 100 GHz channel spacing, > 0 dBm +/- 1.5 dB outputs, and > 50 dB SMSR. Bottom curve (in red): transmission spectra of the etalon

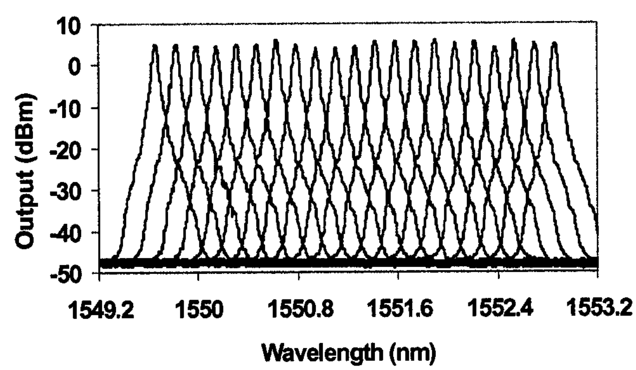


Fig. 9: 21-channel wavelength-switchable operation of a λ-agile source with 20 GHz channel spacing, > 3 dBm +/- 1.2 dB outputs, and > 55 dB SMSR

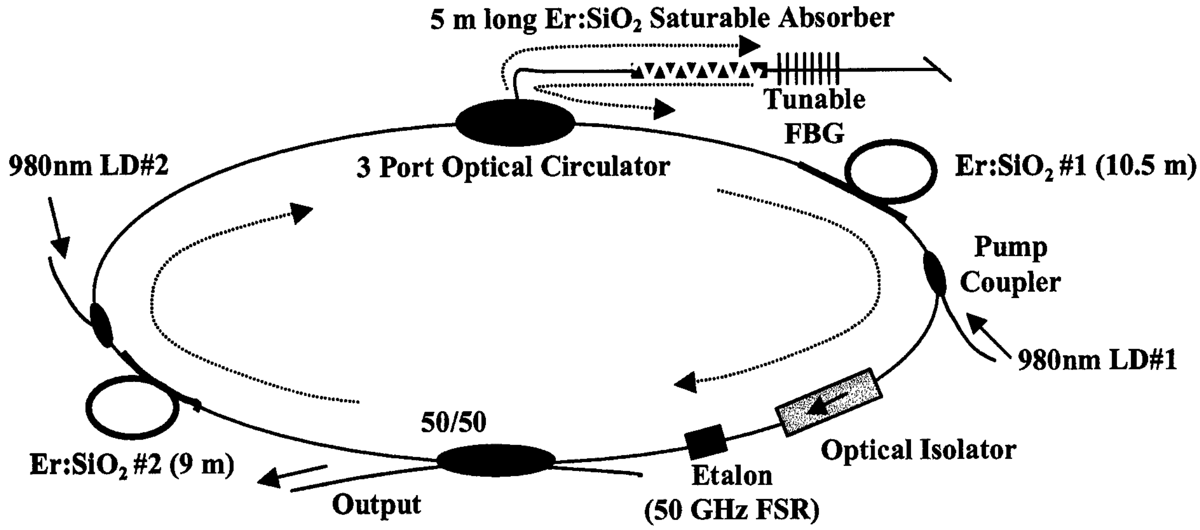
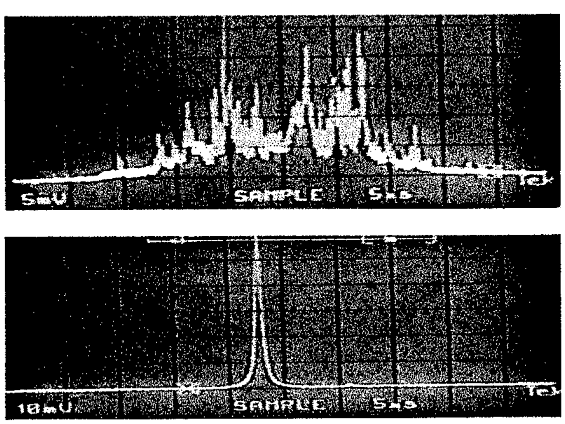


Fig. 10: Schematic of the laser design that was used for demonstrating **single-mode** wavelength-switchable outputs



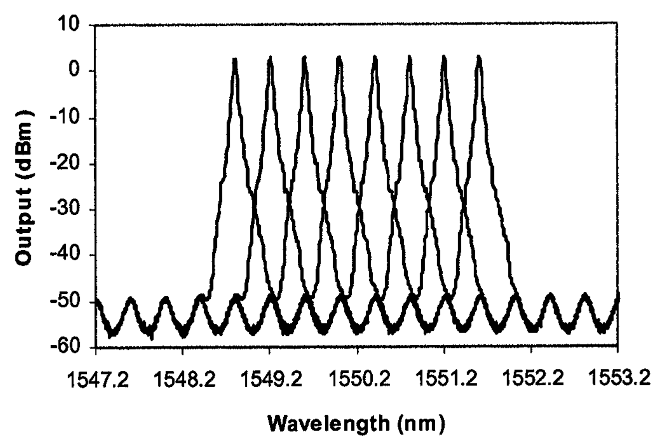


Fig. 11: Scanning Fabry-Perot traces of (a) multimoded laser emission without line-narrowing saturable absorber, and (b) singlemoded emission with 5 m of $Er:SiO_2$ line narrowing absorber

Fig. 12: Tunable WDM outputs at 8 uniquely-selected channels spaced 50 GHz apart, 0.93 dBm ± 0.1 dBm outputs, and > 50 dB SMSRs

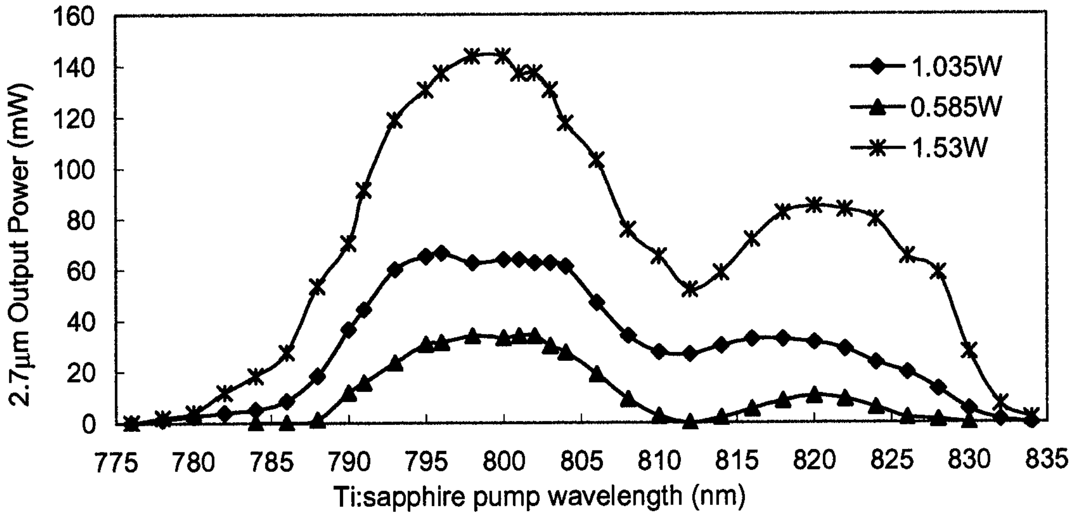


Fig. 13: Variation of 2.7 μm signal as a function of the Ti:sapphire laser wavelength for different pump intensities

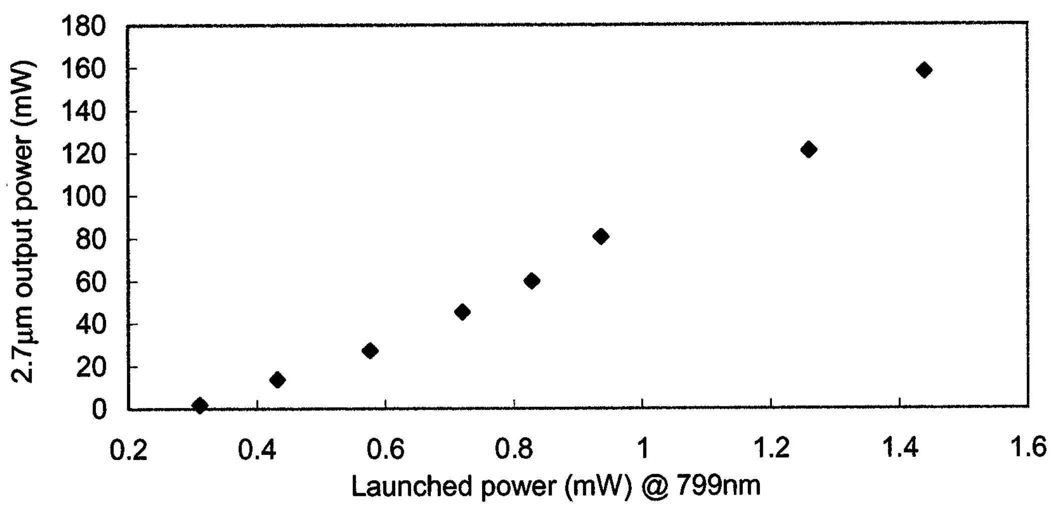


Fig. 14: Output power versus input power for a 799 nm Ti:sapphire pumped 2.7 μm Er:ZBLAN fiber laser

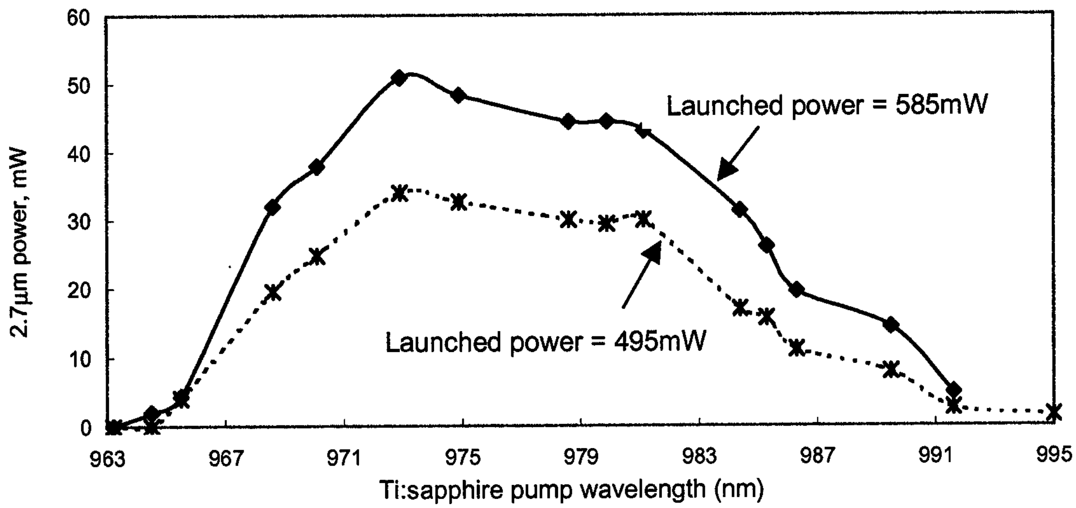


Fig. 15: Variation of 2.7 µm signal with Ti:sapphire laser wavelength for different pump intensities.

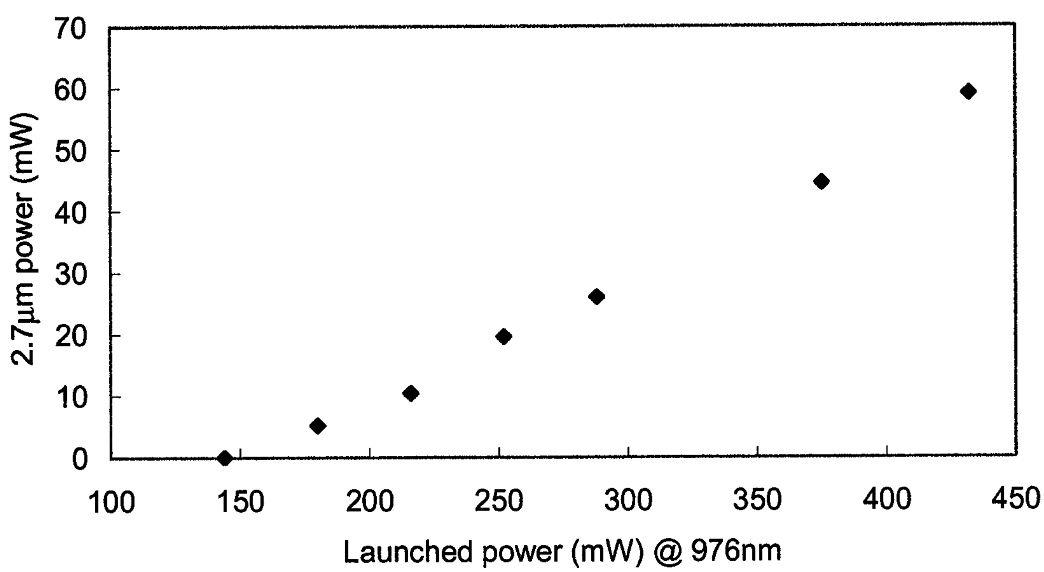


Fig. 16: Output power versus input power for a 976 nm Ti:sapphire pumped 2.7 µm Er:ZBLAN fiber laser

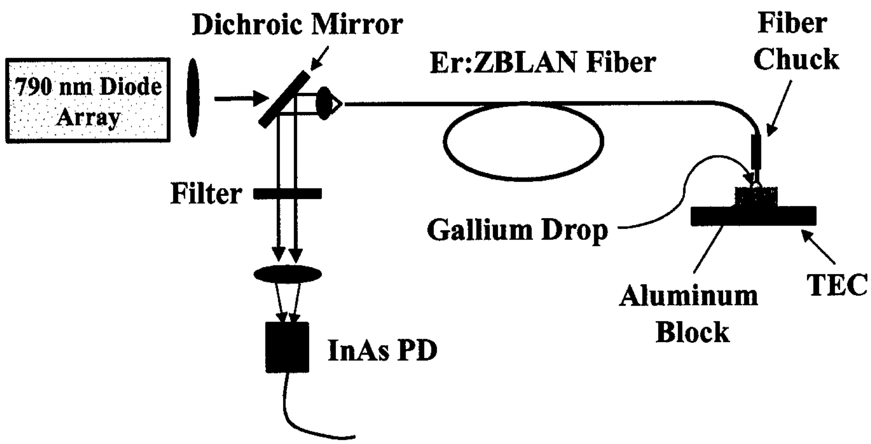
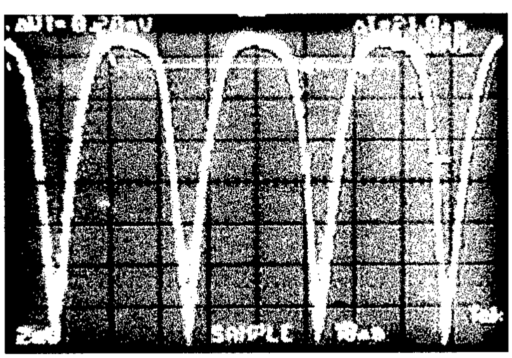
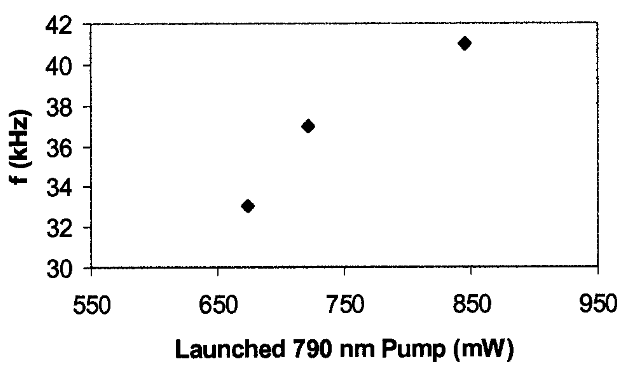


Fig. 17. Schematic of our pulsed (passively Q-switched) mid-IR fiber laser using a butt-coupled liquid gallium mirror





(a)

(b)

Fig 18: Pulsed operation characteristics of a passively Q-switched Er:ZBLAN 2.7 μm fiber laser, showing (a) 7 μs pulsewidths (horizontal scale = 10 μs/div) (b) the repetition rate as a function of the launched pump power.

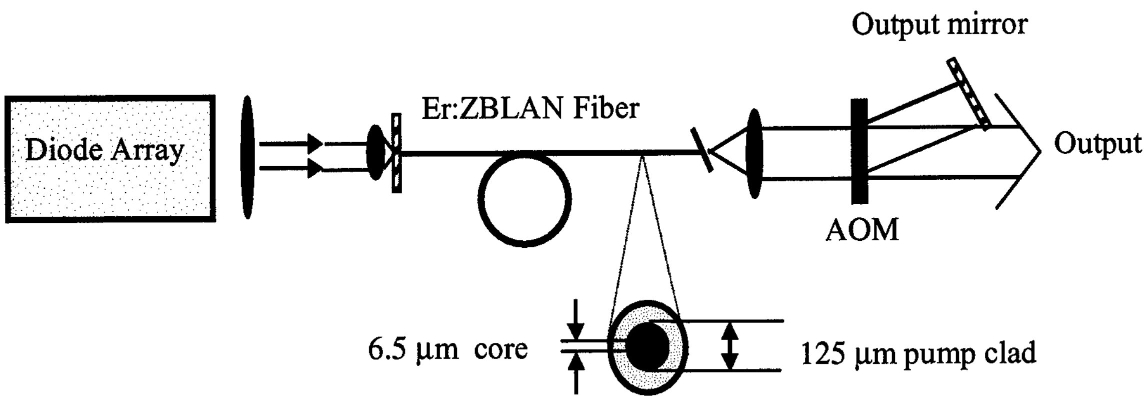


Fig. 19: Schematic experimental setup used for active Q-switching of a 2.7 µm Er:ZBLAN fiber laser

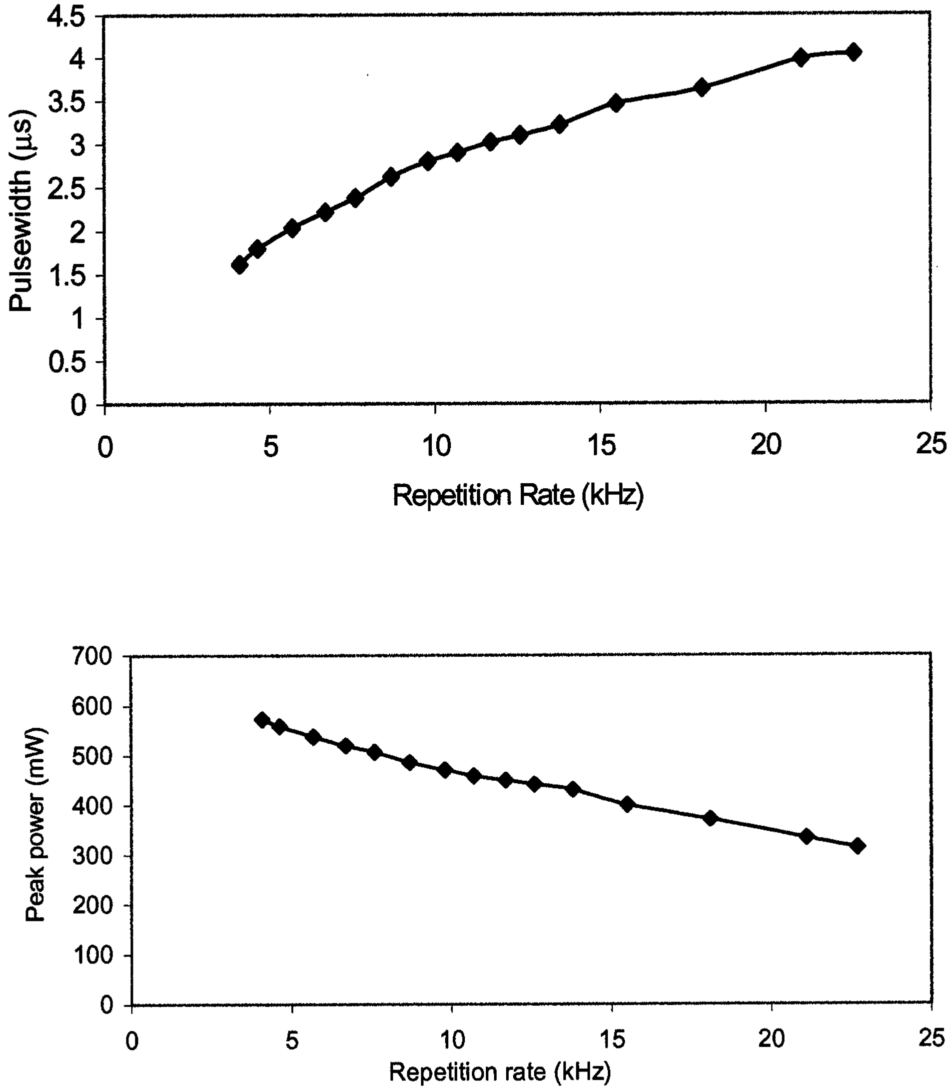
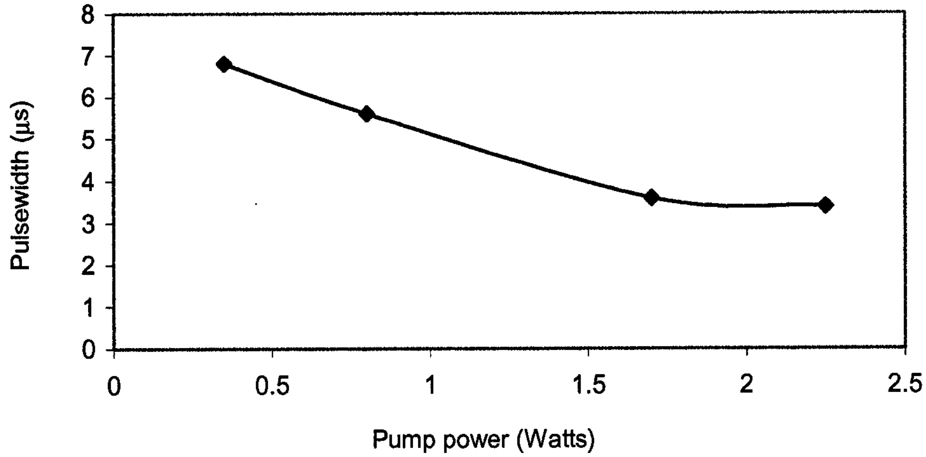


Fig. 20: The dependence of pulsewidth and peak power on the pump repetition rate for our actively Q-switched 2.7 µm Er:ZBLAN fiber laser



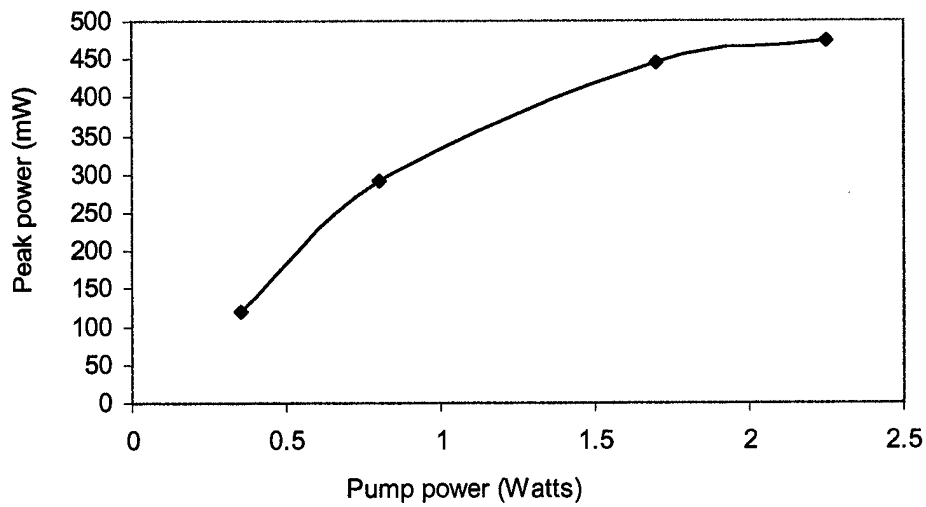


Fig. 21: The dependence of the pulsewidth and peak power on the pump power for our actively Q-switched 2.7 µm Er:ZBLAN fiber laser