

All-fiber sliding-frequency $\text{Er}^{3+}/\text{Yb}^{3+}$ soliton laser

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We report a simple all-fiber sliding-frequency soliton laser incorporating a recently developed low-insertion-loss acousto-optic fiber frequency shifter. The frequency shifter simultaneously provides the spectral filtering and polarizing properties required for pulsed operation to be obtained. © 1995 Optical Society of America

The development of sources of ultrashort pulses based on erbium-doped fibers, for use both as general laboratory tools and for telecommunication applications, has been an area of intense research interest in recent years. Both passively¹ and actively² mode-locked fiber lasers have been demonstrated with a number of cavity configurations and designs. More recently, a new pulse-generation technique based on continuous frequency shifting and spectral filtering of the circulating light within a laser cavity has been developed.³⁻⁵ The laser operation has much in common with the sliding-filter soliton control technique developed by Mollenauer *et al.*⁶ and so has become known as the sliding-frequency soliton laser. Light circulating within the laser undergoes both a frequency shift and a filtering action during each cavity round trip. Cw radiation initially situated at the peak of the gain curve will thus gradually move away from the peak, experiencing progressively higher loss as it does so. Conversely, high-intensity pulses can spectrally reshape themselves after the frequency shift and filtering action because of soliton propagation effects within the fiber cavity. An operating point can be reached at which the opposing spectral shaping effects balance and stable pulsed laser action can be obtained with a corresponding loss advantage relative to the cw case. Consequently, the laser preferentially operates in a pulsed mode. Pulse durations as short as 16 ps have been obtained at pulse burst repetition rates as high as 20 GHz.⁴ By incorporation of a polarizer within the cavity, nonlinear polarization effects have permitted the formation of pulses as short as 7 ps.⁵ Although many of the instabilities inherent in free-running passively mode-locked cavities still persist,^{1,2} the technique offers advantages regarding (i) the self-start threshold, relative to conventional passive mode-locking techniques, and (ii) tolerance to harmonic locking frequency, relative to conventional active mode-locking techniques.^{4,5}

A principal disadvantage of the sliding-frequency technique is the requirement to incorporate either bulk- or integrated-optic frequency shifters, filters, and polarizers within the cavity. Such components are lossy and costly and can give rise to étalon effects that frustrate or hinder mode-locked operation. Recently, progress has been made in developing fiber acousto-optic frequency shifters with acoustically driven four-port null couplers.⁷ Frequency shifts of 10 MHz, with conversion efficiencies greater than 99%, carrier sup-

pression of 30 dB, and insertion loss of 0.1 dB, have been obtained for acoustic drive powers as low as 2 mW. Moreover, the devices also act as tunable optical bandpass filters, can be designed to be polarizing,⁸ and do not give rise to internal backreflections. As such they are ideal as mode-locking elements for sliding-frequency soliton lasers, permitting the construction of truly all-fiber, low-loss laser cavities. In this Letter we describe the construction and performance of such a device, demonstrating the generation of 18–60-ps pulses, electronically controlled wavelength and output coupling tunability, fundamental and harmonic mode locking, and simultaneous bi-directional operation of a completely all-fiber cavity.

The frequency shift laser was configured in a ring geometry (see Fig. 1). The total cavity length was 25 m and, apart from the 7-m $\text{Er}^{3+}/\text{Yb}^{3+}$ amplifier fiber, was constructed entirely from standard telecommunication-grade fiber of anomalous dispersion 16 ps/(nm km). The $\text{Er}^{3+}/\text{Yb}^{3+}$ fiber dispersion was not known but from the fiber design parameters was predicted to be slightly normal, ~ -5 ps/(nm km); the overall cavity dispersion was therefore anomalous. The system was pumped with a diode-pumped Nd:YAG laser capable of delivering as much as 250 mW of pump radiation at 1064 nm.

The four-port, acousto-optic fiber frequency shifter was designed to operate at 11 MHz. A flexural acoustic wave was excited in the coupler waist by a piezoelectric disk with a concentration horn, driven by an

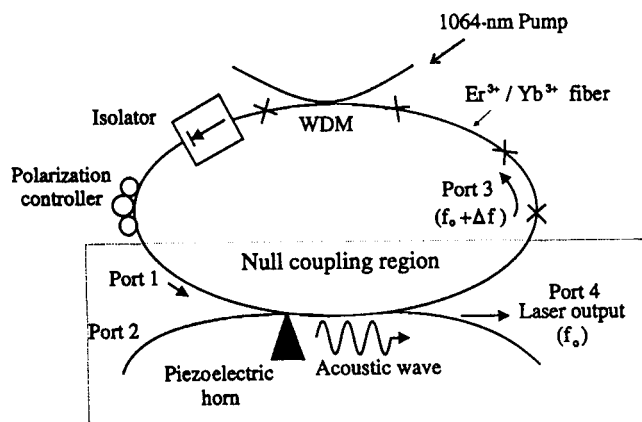


Fig. 1. Laser configuration. In the absence of an acoustic flexural wave, all the light will leave via port 4. WDM, wavelength-division multiplexer.

rf signal. The horn was fixed to the pair of unpre-tapered fibers at one end of the coupler in such a way that the plane of the acoustic wave coincided with the plane of the coupler.⁷ At an appropriate acoustic power, light in the correct polarization state was frequency upshifted and coupled across to port 3. We could obtain 0–97% conversion efficiency by varying the acoustic drive power to the device. Residual unshifted light and light incident upon the wrong polarization axis emerge from port 4 and leave the cavity. Polarization extinction of >17 dB could be obtained by variation of the input polarization state of light to the device. The measured insertion loss of the shifter was 0.1 dB (1 dB when connectorized). We checked the optical filtering response of the frequency shifter on its own by injecting polarized amplified spontaneous emission from the amplifier at port 1 and examining the optical spectrum of the frequency-shifted component. A number of discrete conversion peaks of ~4.5-nm bandwidth were discovered with a spacing of ~10 nm (see Fig. 2). The origin of the additional peaks is thought to be attributed to the lack of uniformity within the taper waist and the taper transitions themselves satisfying multiple resonances within the null coupler. It should be possible to suppress these undesirable peaks by exercising greater control over (i) the uniformity of the waist and (ii) the profile of the taper transitions of the null taper coupler. By tuning the frequency of the acoustic drive we proved it possible to tune the position of the transmission peaks continuously across the entire erbium bandwidth from 1538 to 1570 nm (see Fig. 2); however, the relative amplitudes of the multiple transmission peaks changed slightly, and this hindered our ability to tune the laser output continuously across the erbium band.

Feedback into the laser was from the frequency-shifted port, and the laser output was taken from the unshifted port. Cross coupling of the frequency-unshifted beam into the frequency-shifted port was ~-40 dB, and laser action was completely frustrated when no acoustic power was applied to the device. By varying the acoustic power we could vary the output coupling from the laser, and by tuning the acoustic frequency we could tune the wavelength of operation. A polarization controller was positioned in front of the frequency shifter to control the polarization state of the light incident upon the device. Unidirectional operation of the laser was ensured by the incorporation of an optical isolator into the loop. We later removed the isolator from the cavity to examine whether pulsed bidirectional operation of the device could be obtained and to demonstrate the operation of a truly all-fiber cavity.

The laser performance was investigated for a wide range of system parameters, and a number of operating regimes were identified. Pulsed operation was by far the preferred mode. The self-start mode-locking threshold occurred typically at a launched pump power of 25 mW. The maximum output power was 20 mW, and the slope efficiency was 8–9%. Both 35–40-ps chirped pulse generation and close to transform-limited pulsed operation at 18 ps could be obtained (Fig. 3). On self-start mode locking a large number of pulses were generally formed within the cavity, and the

chaotic temporal behavior characteristic of soliton fiber lasers was obtained.^{1,2} However, by appropriate control of the pump two stable regimes of operation could be identified (Fig. 4): At low pump powers [Fig. 4(a)] a single pulse could be made to circulate within the cavity (fundamental mode locking), and at higher pump powers [Fig. 4(b)] harmonic mode locking near 500 MHz could be obtained. Output pulse energies were dependent on the laser operating condition (i.e., birefringence, frequency shift drive conditions) but were typically a few picojoules. Note that harmonic mode locking could be sustained only over a narrow range of launched pump power (60 ± 2 mW) for which

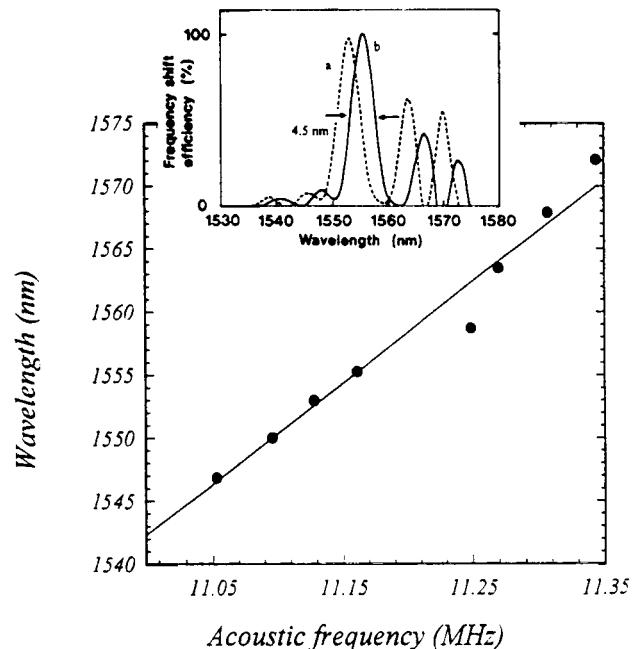


Fig. 2. Tuning curve and filter characteristics of the null coupler frequency shifter. The change in amplitude of the transmission peaks corresponds to two different acoustic drive frequencies: at 11.09 MHz (curve a) and at 11.13 MHz (curve b).

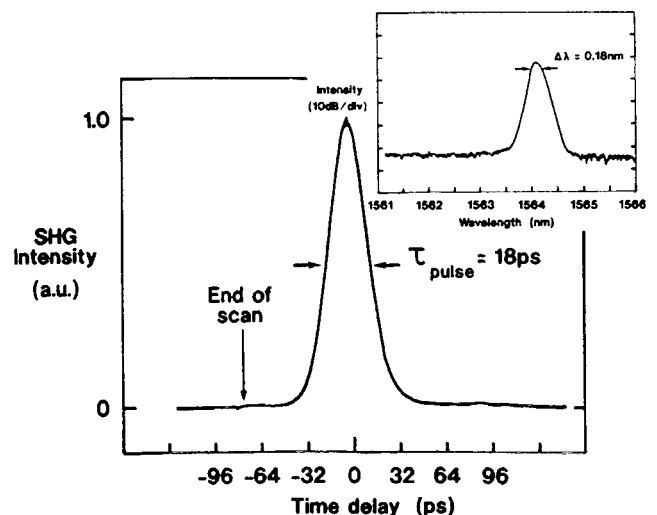
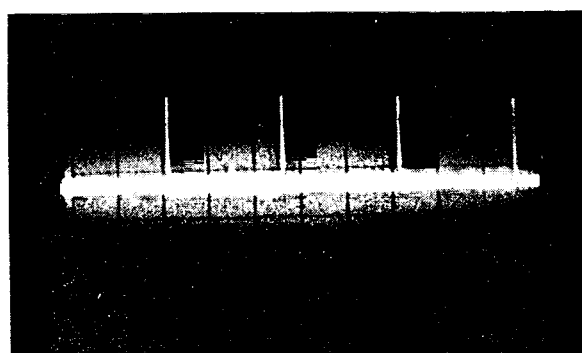
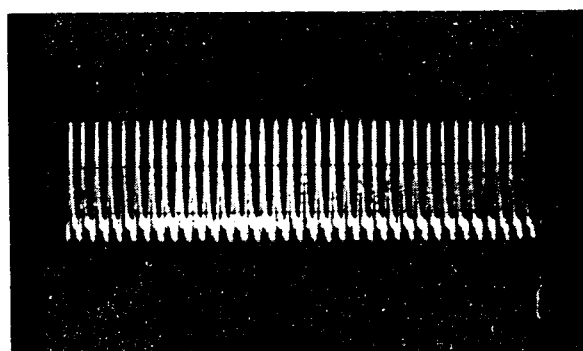


Fig. 3. Autocorrelation and spectrum of 18-ps pulses. The apparent small pedestal level across the scan is an artifact of the measurement system; the pulses are generally pedestal free. SHG, second-harmonic generation.



← 500 ns →

(a)



← 50 ns →

(b)

Fig. 4. Time-domain behavior of the laser. (a) Fundamental: interpulse spacing 122 ns. (b) 500-MHz harmonic: interpulse spacing 2 ns.

the circulating power was sufficient to support the harmonic number of pulses (~ 70) circulating within the cavity. The operation at ~ 500 MHz was observed previously in passively mode-locked fiber lasers and is thought to be due to the soliton electrostriction effect.⁹ The tendency for this particular laser to operate in this mode seemed particularly strong, and, indeed, as well as single pulses locking in at 500 MHz we also observed pulses locking together in bunches at 500 MHz. The spacing of the pulses within these 500-MHz bunches was ~ 120 ps. Clustering of pulses with 120-ps separation (8-GHz burst rate) was also observed at the cavity round-trip rate. Clustering of pulses at similarly high frequencies within such lasers has also been observed by other authors, who employed bulk frequency shifting and filtering components.⁴ Electronic tuning of the laser wavelength was attempted by adjustment of the frequency of the acoustic drive to the null coupler. The laser could

be made to operate over the entire wavelength range; however, continuous wavelength tunability was impaired because of the relative change in the amplitude of the transmission peaks. Two such cases are shown in Fig. 2, where the transmission peaks of the device for two different acoustic drive frequencies at 11.09 and 11.13 MHz are shown. The change in amplitude for a given transmission peak as it is tuned is as high as 40% and does not vary smoothly over more than a few nanometers because of our present lack of control over the uniformity of the taper waist. This means that continuous wavelength tunability could be obtained only over a 1–2-nm range before discrete jumps in the laser output occurred.

Finally, we removed the isolator from the cavity to examine whether mode-locked operation could be obtained without enforcing unidirectional operation in a truly all-fiber cavity. Stable, bidirectional mode locking was obtained with no readily discernible difference in the pulse output from the two counterpropagating beams.

We have demonstrated a simple all-fiber, frequency-shift soliton laser based on a low-loss fiber frequency shifter that in addition provides the spectral filtering required for support of pulsed operation. The laser is considerably simpler than the equivalent fiber laser built with bulk- or integrated-optic components. Furthermore, we have observed (i) electrostrictive repetition-rate stabilization, (ii) wavelength tunability, and (iii) bidirectional pulsed laser operation. The results demonstrate the great potential of such frequency shifters in all-fiber laser systems.

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