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Sliding Frequency Er^{3+}/Yb^{3+} Soliton Laser Employing All-Fibre Acoustooptic Frequency Shifting/Tunable Filter

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Abstract

We report for the first time a simple all-fibre sliding frequency soliton laser incorporating a recently developed low-loss acoustooptic fibre frequency shifter, that simultaneously provides the spectral filtering and polarising properties required to obtain pulsed operation.

The development of sources of ultrashort pulses based on erbium doped fibres for use both as general laboratory tools and for telecommunication applications has been an area of intense research interest over recent years. Both passively [1] and actively mode-locked fibre lasers [2] have been demonstrated and developed employing a number of cavity configurations and designs. More recently, a new pulse generation technique based on continuously frequency shifting and filtering the circulating optical power within a laser cavity has been developed [3,4]. The laser operation has much in common with the sliding filter soliton control technique developed by Mollenauer [5] and hence it has become known as the sliding frequency soliton laser. The reason that such lasers tend to operate in a pulsed mode lies in the fact that high intensity pulses can reshape themselves spectrally following the combined action of filtering and frequency shifting due to soliton propagation effects within the anomalously dispersive fibre comprising the laser cavity. A stable operating point can be found at which the filtering and frequency shift per round trip are balanced by the spectral reshaping. Conversely, CW light is continuously frequency-shifted each time it passes around the cavity such that its wavelength moves from the filter transmission peak and sees higher loss. Consequently there is a loss advantage for the laser to operate in a pulsed mode. Pulse durations as short as 16 ps have been obtained using the basic techniques at pulse burst repetition rates as high as 20 GHz [4]. By incorporating a polariser within the cavity, nonlinear polarisation effects have enabled pulses as short as 7 ps [4]. Although many of the instabilities inherent within free running passively mode-locked cavities still persist, the technique offers advantages regarding a) self-start threshold relative to conventional passive mode-locking techniques and b) tolerance to harmonic locking frequency relative to conventional active mode-locking techniques. Another potential disadvantage is the requirement to incorporate either bulk or integrated optic frequency shifters, filters and polarisers within the cavity. Such components are lossy and costly, and can additionally give rise to etalon effects within the cavity that frustrate or hinder mode-locked operation.

Recently, impressive progress has been made in the development of fiber acoustooptic frequency shifters using acoustically driven, four-port null couplers [6]. Losses as low as 0.1 dB and frequency conversion efficiencies higher than as 99% with carrier suppression of >30 dB have been obtained for acoustic drive powers as low as 2 mW at frequency shifts as high as 10 MHz. Moreover, the devices also act as tunable optical bandpass filters, can be designed to be polarising, and do not give rise to internal back reflections. As such they are ideal as modelocking elements for sliding frequency soliton lasers, permitting the construction of truly all-fibre, low-loss laser cavities. In this paper we describe the construction and performance of such a device, demonstrating the generation of 18-60 psec pulses, electronically controlled wavelength and output coupling tunability, fundamental and harmonic mode-locking and simultaneous bi-directional operation of a completely all-fibre 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 7m Er^{3+}/Yb^{3+} amplifier fibre, was constructed entirely from standard telecommunication grade fibre of dispersion 16 ps/(nm.km). The Er^{3+}/Yb^{3+} fibre dispersion was not known but from the fibre 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 upto 250 mW of pump radiation at 1064 nm. The four-port, acoustooptic fibre frequency-shifter was designed to operate at 11 MHz. With appropriate acoustic power coupled into the device, light in the correct polarisation state is frequency upshifted and couples across to port 3. Between 0 and 97% conversion efficiency could be obtained by varying the magnitude of the acoustic drive to the device. Residual unshifted light and light incident on the wrong polarisation axis emerges from port 4. Greater than 17 dB of polarisation extinction could be obtained by varying the input polarisation state of light to the device. The measured insertion loss of the shifter was 0.1 dB (1 dB when connectorised). The optical filtering response of the device was examined by injecting polarised ASE from the amplifier at port 1 and examining the optical spectrum of the frequency shifted component. A number of discrete conversion peaks of $\sim$4.5 nm bandwidth were discovered with a spacing of about 10 nm. The origin of the additional peaks is thought to be multiple resonances occurring within the tapered transition regions of the null coupler. It should be possible to suppress these undesirable additional peaks by more refined tapering of the coupler. By tuning the frequency of the acoustic drive it proved possible to continuously tune the position of the transmission peaks across the entire erbium bandwidth from 1538-1570 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 to the device we could vary the output coupling from the laser and by tuning the acoustic frequency we could tune the wavelength of operation. A polarisation controller was positioned in front of the frequency shifter to control the polarisation state of the light incident to the device. Unidirectional operation of the laser was ensured by the incorporation of an optical isolator into the loop. The isolator was later removed from the cavity to examine whether pulsed bi-directional operation of the device could be obtained and to demonstrate the operation of a truly all-fibre 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 was typically 30 mW of input pump. The maximum output power was 20 mW and slope efficiency 8-9%. Both 35-40 ps chirped pulse generation and close to transform-limited pulsed operation at 18 ps could be obtained. Generally the laser operated with a large number of pulses within the cavity and exhibited chaotic time domain behaviour characteristic of a typical passive soliton fiber laser. However, for certain operating parameter ranges, fundamental mode locking (low pump powers) (Fig.3a) and harmonic modelocking around 500 MHz could be obtained (Fig.3b). The operation around 500 MHz has been observed previously in passively mode-locked fibre lasers and is thought to be due to the soliton electrostriction effect [7]. 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 into 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 has also been observed by other authors within such lasers, employing bulk frequency shifting and filtering components [4]. Electronic tuning of the laser wavelength was attempted by adjusting the frequency of the acoustic drive to the null coupler. The laser could be made to operate over a wide wavelength range from 1543-1565 nm; however, continuous wavelength tunability was obtainable only over a 1-2 nm range due to the multiple peak nature of the shifter's filter response. Large improvements in the continuous tuning range are expected by optimising the design of the null coupler.

Finally, we removed the isolator from the cavity to examine whether mode-locked operation could be obtained without enforcing unidirectional operation in a completely all-fibre cavity. Stable, bi-directional modelocking was obtained with no readily discernible difference in the pulse output from the two counterpropagating beams, despite the fact that one beam is experiencing an up-shift and the other a down-shift in frequency per round trip.

In conclusion, we have demonstrated a simple all-fibre, frequency-shift soliton-laser based on a low-loss fibre frequency-shifter that in addition provides the spectral filtering required to support pulsed operation. The laser is considerably simpler than the equivalent fiber laser built using bulk or integrated optic components. Furthermore we have observed for the first time electostrictional repetition rate stabilisation within such a laser, wavelength tunability and bi-directional pulsed laser operation. The results demonstrate the great potential of such all-fibre tapered devices in all-fibre laser systems.

References

[1] D. J. Richardson et al, *Electron. Lett.*, **27**, 730 (1991).
[2] R. P. Davey et al, *Electron. Lett.*, **28**, 482 (1992).
[3] H. Sabert et al, *Electron. Lett.*, **29**, 2122 (1993).
[4] F. Fontana et al, *Electron. Lett.*, **30**, 321 (1994).
[5] L. F. Mollenauer et al, *Opt. Lett.*, **17**, 1575 (1992).
[6] T. A. Birks et al, *Opt. Lett.*, **19**, 1964 (1994).
[7] A. B. Grudinin et al, *Electron. Lett.*, **29**, 1860 (1993).

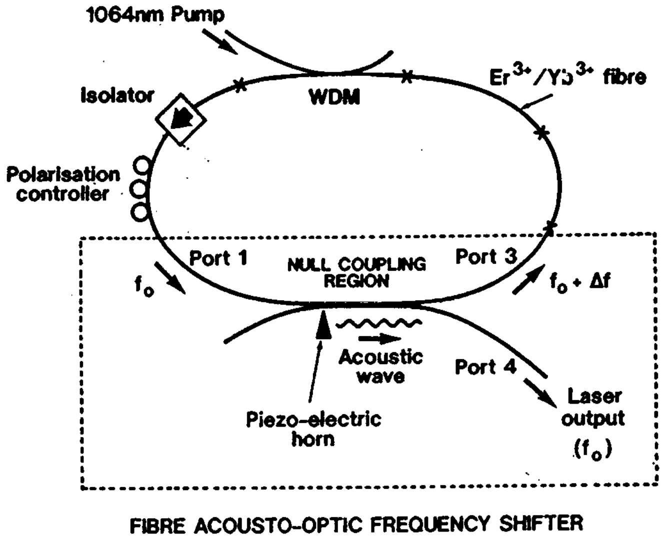

Fig.1 Laser configuration

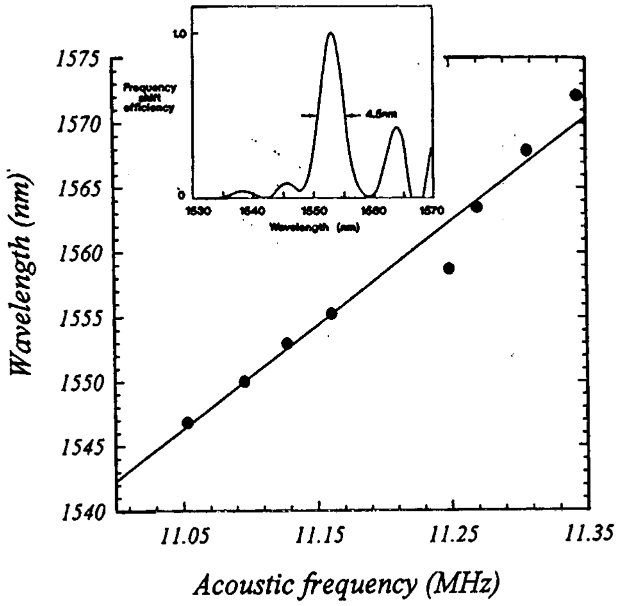

Fig.2 Tuning Curve and filter characteristic

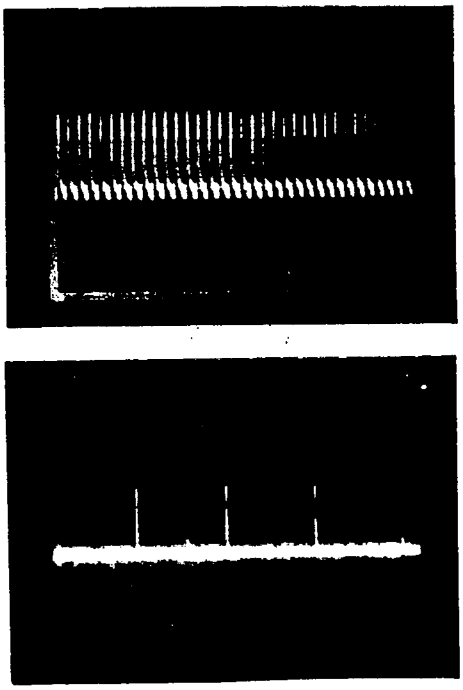

Fig.3 Time domain behavior
(a) Fundamental
(b) 500 MHz harmonic

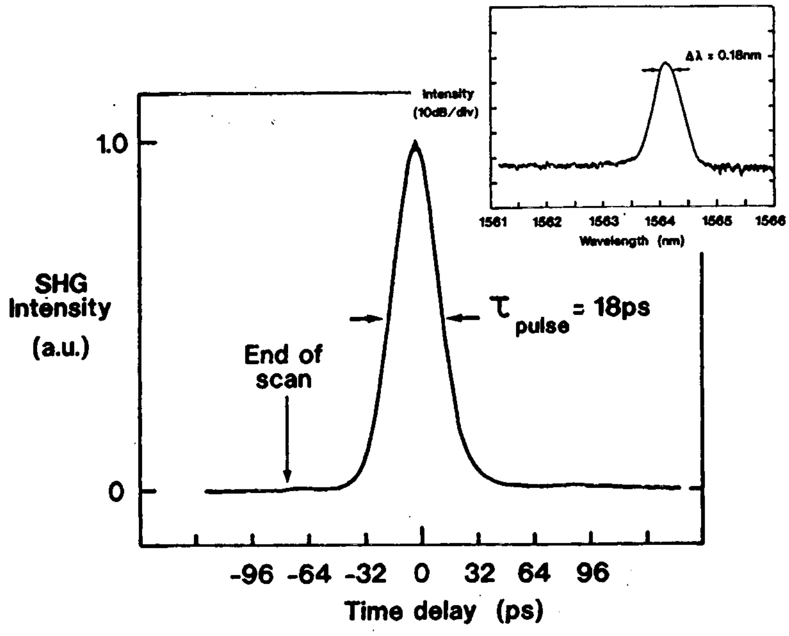

Fig.4 Autocorelation and
spectrum of 18 ps pulses