Passive harmonic modelocking of a fibre soliton ring laser

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Indexing term: Lasers

The Letter reports passive, harmonic repetition rate stabilisation at frequencies ranging from 200MHz to 1GHz within a passively modelocked erbium doped fibre ring laser generating 1.4 ps transform-limited soliton pulses. From observations, it is postulated the likely origin of the self-stabilisation is the long-range repulsive interaction of soliton pulses due to transverse acoustic wave excitation.

Passively modelocked fibre soliton lasers [1–7] (PSL) have a range of properties e.g. simplicity, tunability, pico- and femtosecond operation, that make them attractive sources for laboratory, telecommunication and signal-processing applications.

The energy quantisation effect [4] caused by the soliton regime of operation of PSLs results in excellent individual pulse parameter stability, but also leads to pulse repetition rate instabilities which can be problematic for many applications. One solution is to operate the laser with just a single pulse within the cavity, but this generally leads to low repetition rates (~5MHz) and correspondingly low output powers unless short cavities of a few metres length are used. Other techniques involving additional intracavity cavities [5], extra-cavity feedback [6] or intracavity modulation [7] have been demonstrated, enabling higher harmonic modelocking, and higher output powers to be obtained: however, these techniques would appear to be difficult to implement in a practical system.

We present a completely passive fibre laser scheme capable of stable operation at a very high harmonic of the cavity round trip frequency.

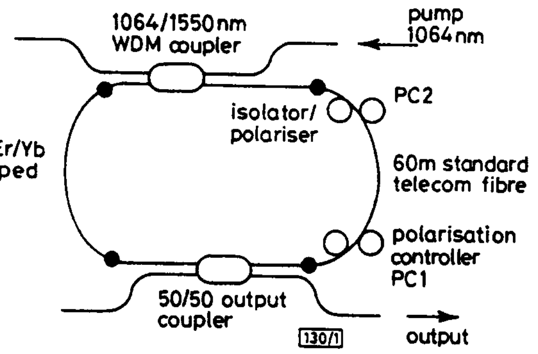

Fig. 1 *Experimental configuration*

The laser cavity configuration is shown in Fig. 1 and is similar to that described elsewhere [3]. The laser cavity comprises 4m of Er^{3+}/Yb^{3+} codoped fibre with Er^{3+} and Yb^{3+} (ion concentration 800*ppm* and 5000*ppm*, respectively). 60m of standard telecom fibre ($NA = 0.1$, $\lambda_{co} = 1230$nm, $D = -17$ps/nm.km) and a polarisation-dependent isolator. Two polarisation controllers are used to set the appropriate state of polarisation required for self-start modelocking. With 500mW pump power from a conventional Nd:YAG laser we obtained 35 mW output power at 1540nm. At such pump powers the modelocking self-starts at practically any position of PC2, provided that PC1 is suitably set.

In common with other passively modelocked fibre lasers [6] the present laser can operate in two modelocked modes: a 'tightly bunched' pulsed mode with 3–10nm spectral bandwidth at the fundamental frequency (3.21MHz), or to produce 1.4ps solitons at an ill-defined repetition frequency owing to complicated pulse motions, as described in [2].

However, at certain positions of PC2 we discovered an interesting and significant feature of the laser behaviour, which permitted high harmonic modelocking. At some fixed pump power and position of the PCs the laser produced 'tightly-bunched' pulses. If the position of PC1 is then suitably adjusted (leaving the position of PC2 unaltered), we observed a break up of the pulse bunches into a stable temporal pattern as shown in Fig. 2*a*. The transformation from the bunched pulse regime to the stable harmonic pattern occurred over a period of several seconds with respect to the change in position of PC1. Observing the dynamics of the process on an oscilloscope, this transient regime is characterised by a temporal stretching of the original bunched pulses at a speed of ~10ns/s (or 2m/s in ordinary units) until the whole time domain is occupied. This is then followed by a gradual rearrangement of pulse separations until a stable harmonic pulse train is formed. Note that we never observed instances in which individual time-slots were left unoccupied within the train as was observed using other stabilisation techniques [5, 7]. Fig. 2*b* and Fig. 2*c* represent RF and optical spectra, respectively, of a 914MHz soliton train so obtained. Autocorrelation measurements prove that the laser produces transform-limited, pedestal-free 1.4 ps pulses.

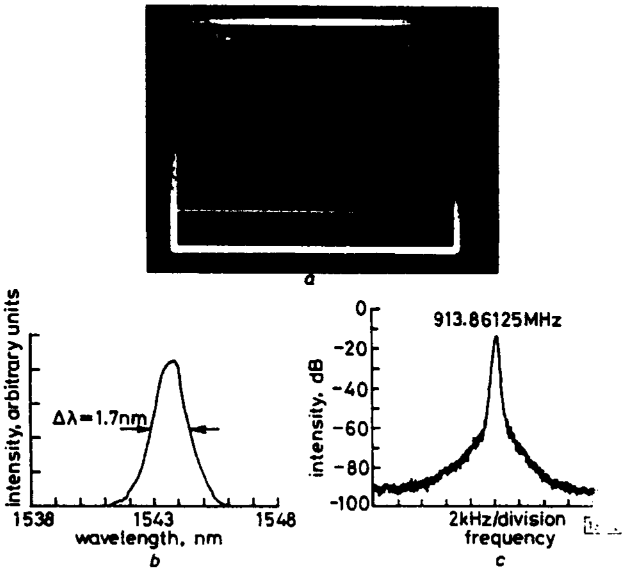

Fig. 2 *914MHz harmonically modelocked fibre laser*

a Optical pulse train
b Optical spectrum of 1.4ps solitons
c RF spectrum of laser output (spectral resolution : 300Hz)

By changing the pump power and hence the circulating intra avity power we observed several stable harmonic operat quencies ranging between 200MHz and 1GHz (Fig. gradient allows us to estimate the energy of the individual pulses as 23pJ, close to that of the energy of a 1.4ps fundamental soliton (21pJ). Note also that such self-stabilisation does not depend on the cavity length: the effect took place for a number of cavities of substantially different lengths. Indeed, the repetition frequency of the trains self-adjusted to any long-term drift in cavity length enabling the laser to be operated at such high frequencies for periods of hours providing that the laser pump power is adequately stabilised.

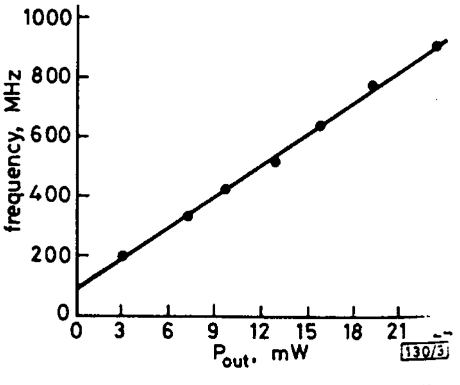

Fig. 3 *Dependence of frequency of stable harmonically modelocked operation on output laser power*

The effective velocity difference of 2m/s measured above during the early stages of the harmonic train formation process can be caused either by a change in refractive index as seen by the individual pulses or by a variation in their central frequencies. Knowing the group velocity difference we can estim der of magnitude of the required refractive index cha quency difference to be $\sim 10^{-8}$ and $\sim 10^{9}$Hz respectively.

There are two main effects that could cause such a velocity difference for widely spaced pulses: the so called 'long-range' soliton interaction caused by the electrostrictional excitation of transverse acoustic waves [8,9] (the resulting transverse acoustic wave generated at a given point in the fibre leads to a temporal change in the refractive index of the core and thus depending on the relative timing delay exerts either an attractive or repulsive effect on subsequent pulses) and the soliton self-frequency shift effect (SSFS) [10]. For the given fibre length, diameter and dispersion and by assuming the parameters of the generated pulses we can estimate the refractive index change due to the transverse acoustic perturbation as being equal to $\sim 10^{-12}$ with the frequency shift per round trip due to the acoustic effect and the Raman gain (neglecting any gain-pulling effects) is equal to $\sim 10^6$Hz and $\sim 10^9$Hz, respectively. These estimations and our additional experimental observations lead us to assume that at certain PC positions the laser can operate in a multistable (with respect to wavelength) regime. By rotation of the PC, the system is turned into a single-wavelength mode and because only one wavelength is now stable with respect to the laser gain/loss conditions, pulses with the 'wrong' wavelength change their central frequency via SSFS in order to maintain the total intracavity energy and move towards the stable mode. This leads initially in a slow motion of the pulses and results in an almost uniform distribution of the pulses over the round-trip time as observed experimentally.

Each optical pulse excites an acoustic wave travelling across the fibre core causing phase modulation which affects subsequent pulses. Numerical estimations, based on the results of [8,9] show that a repulsive force, which may result in repetition rate self-stabilisation, occurs for frequencies below 1GHz and greater than 2GHz, in good agreement with the experimentally observed repetition frequency range. The rather low depth of phase modulation ($\sim 5 \times 10^{-3}$rad/km) accounts for the relatively large observed jitter of 10ps.

In conclusion we have observed repetition rate self-stabilisation at the 285th harmonic of the fundamental frequency (914MHz) in a simple passively modelocked fibre ring laser. In our opinion the key physical mechanism of the phenomenon is the long-range soliton interaction effect. We have presented a qualitative explanation of the observed phenomena, however further experimental and theoretical studies need to be performed to fully validate its origin.

13 August 1993
Electronics Letters Online No: 19931219

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Singlemode emission from a passive-antiguide-region vertical-cavity surface-emitting laser

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Indexing terms: Vertical cavity surface emitting lasers, Laser diodes

A novel passive-antiguide buried-heterostructure vertical-cavity surface emitting laser (VCSEL) is demonstrated which emits a single fundamental mode at high currents for an aperture as large as 16μm diameter. A simple theoretical calculation is performed and agrees well with the experimental results.

Vertical-cavity surface-emitting lasers (VCSEL) are very promising for numerous applications in optical interconnects, optical recording and optical communications [1–3]. Most of these applications require VCSELs to have stable single-transverse-mode emission with a predetermined polarisation direction. In addition, it is desirable to have a large-aperture laser such that high power and low beam divergence can be obtained. Though many efforts have been made, none of them can achieve singlemode emission at high currents [4–6]. Recently, we have reported a novel buried-heterostructure (BH) VCSEL regrown by metal organic chemical vapour deposition (MOCVD) [7]. We achieved a very low threshold current of 0.8mA and a threshold current density of 490A/cm^2 with 8 and 32μm-diameter BH VCSELs, respectively. Nearly all the VCSELs emit with a linear polarisation at a predetermined direction in the $[0\underline{1}1]$ crystal orientation. The BH VCSEL is designed with a novel transverse-mode selection mechanism with the use of a passive antiguide region (PAR). In this Letter we present experimental results on the modal behaviour at high currents of large-aperture PAR VCSELs. In addition we present a simple one-dimensional (1-D) analysis of our novel laser structure.

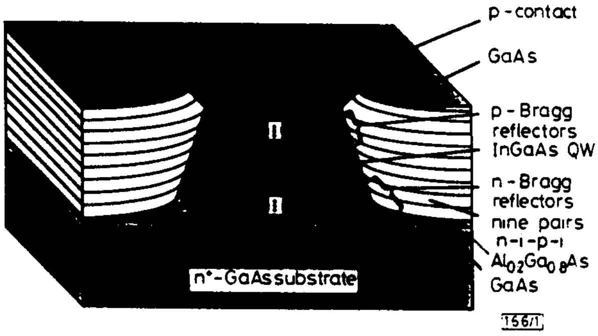

Fig. 1 *Schematic diagram of buried-heterostructure vertical-cavity surface-emitting laser (VCSEL)*

Regrowth includes nine periods of alternating 0.4μm-thick *n-i-p-i*-doped $Al_{0.2}Ga_{0.8}As$ layers sandwiched between two 0.2μm undoped GaAs layers to form current-blocking antiguide cladding around laser

The laser design and fabrication were described in detail in our previous publication [7]. Fig. 1 shows a schematic diagram of the laser structure. The heterostructure was grown by molecular beam epitaxy. Laser posts were formed by dry and wet etching through the active region to obtain both electrical and optical confinements. Current-blocking cladding consisting of lightly *n-i-p-i*-doped $Al_{0.2}Ga_{0.8}As$ surrounding the VCSEL posts was regrown by MOCVD. In this design the equivalent refractive index of the distributed Bragg reflector (DBR) region is less than that of the regrown cladding region. Thus, a passive-antiguide structure is formed effectively around the laser cavity in the transverse direction. This PAR structure introduces higher losses to the high-order transverse modes and thus a single fundamental mode emission can be achieved. Additionally, the tapered shape formed by wet etching also acts as an equivalent aperture which suppresses further the high-order transverse modes of the laser. All the