Tunable Transform-Limited Pulse Generation Using Self-Injection Locking of an FP Laser

L. P. Barry and R. F. O'Dowd, J. Debau, and R. Boittin

***Abstract*—Wavelength-tunable, near transform-limited pulses have been generated using a Fabry–Perot laser diode coupled to a fiber loop containing a fiber Fabry–Perot resonator (FFPR) and a polarization controller. The ratio of transmitted to reflected light from the loop can be adjusted using the polarization controller. Single-mode operation of the gain-switched laser is achieved by self-injection locking, which is induced by light reflected from the fiber loop. The resulting output pulse has a time-bandwidth product of 0.4 and is tunable over about 15 nm by varying the tuning voltage of the FFPR.**

Introduction

A SOURCE of wavelength-tunable, transform-limited optical pulses based on the semiconductor laser diode is vitally important for the development of wavelength division multiplexed (WDM) soliton communication systems [1]. Solitons are suitable for WDM systems as they completely recover from collisions with each other. There are basically two approaches to produce transform-limited pulses from laser diodes suitable for transmission as solitons. One is to use mode-locking of an external-cavity laser, which normally requires precise optical alignment. Using this method, a tunable source of near transform-limited pulses has been demonstrated [2] by mode-locking a two-section distributed Bragg reflector (DBR) laser coupled to a fiber external-cavity. Wavelength tuning of the output pulses was achieved by varying the Bragg current of the laser. The second method of generating transform-limited pulses is to gain switch a distributed feedback (DFB) laser diode and then use a narrow band optical filter and/or dispersion-shifted fiber to reduce the time–bandwidth product to achieve transform-limited pulses [3]. When gain switched, the optical spectrum of the single-mode DFB laser is broadened due to chirp. The optical filter reduces the bandwidth of the spectrum. As the DFB laser is a single-mode device, there is only one wavelength (position of the optical filter) at which the output is optimum. This limitation may be overcome by using a gain-switched FP laser locked into single-mode operation using optical feedback. Cavelier *et al.* [4] have demonstrated this at a wavelength of 1.3 μm using a diffraction grating at the end of an external cavity to select one laser mode. In their work, pulse compression using dispersion-shifted fiber is required to achieve pulses that approach the transform limit.

In the present work, tunable, near transform-limited pulses have been achieved by the novel idea of coupling a FP laser diode to a fiber loop reflector containing a tunable fiber Fabry–Perot resonator (FFPR) [5] and a polarization controller. The laser is locked into operation at one mode by self-injection locking [6], which is induced by output light being fed back to the laser from the fiber loop. It should be noted that, unlike for mode-locking using an external-cavity laser, no antireflection coating is required on the internal FP laser diode. The polarization controller is used to vary the ratio of transmitted to reflected light from the fiber loop reflector [7], [8]. Wavelength tuning of the output pulse is achieved by using the FFPR.

Experimental Setup

The experimental setup is as shown in Fig. 1. The semiconductor laser diode used is a high-speed, 1.55 μm, P-side up, FP quantum well laser diode. The laser has a threshold current of 5.1 mA. It has a relaxation oscillation frequency of 10.5 GHz and a 3-dB down frequency of 6 GHz, at a bias current of 30 mA (the 3-dB frequency is lower than the relaxation frequency due to the very high roll-off of this laser). The laser was gain switched using a 500-MHz step recovery diode (SRD) module from Hewlett Packard (HP 33004C). The electrical pulses are transformed into a shape more suitable for gain switching using a 3.7- to 8.4-GHz electrical isolator [9]. This isolator was found to produce the optimum electrical pulse (an isolator at lower frequencies will not sufficiently alter the pulse, while one at higher frequencies will result in too much power loss). The isolator results in an overshoot of the usually negatively going pulse from the SRD. The advantage of this is that the carrier density in the active area of the laser diode is quickly reduced, which leads to a reduction of the pedestal problem usually associated with the falling edge of gain-switched optical pulses. As the diode is P-side up, a pulse invertor with a rise time < 20 ps is used. A variable attenuator is placed before the laser

Manuscript received March 1, 1993; revised May 31, 1993.
L. P. Barry and R. F. O'Dowd are with the Department of Electronic and Electrical Engineering, University College Dublin, Belfield, Dublin 4, Ireland.
J. Debeau and R. Boittin are with CNET–LAB/SMR/ESO, B.P. 40, 22300 Lannion, France.
IEEE Log Number 9212038.

1041-1135/93$03.00

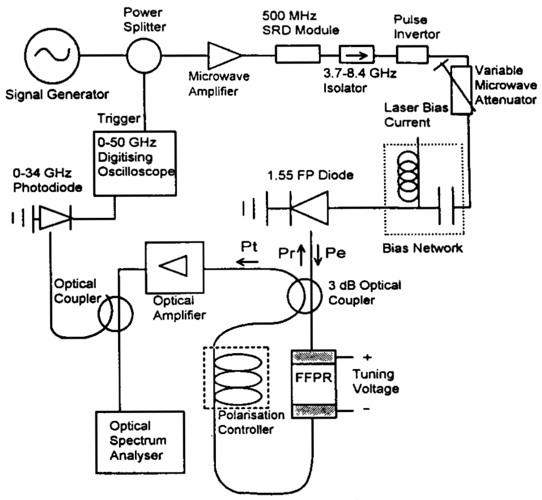

Fig. 1. Experimental configuration used for self-injection locking of a gain-switched FP laser using fiber loop reflector. The fiber loop contains a tunable FFPR and a polarization controller.

to adjust the injected current to the laser diode. The laser chip is mounted directly at the end of a 50-Ω transmission line without a matching resistor. This almost doubles the pulse drive current to the laser for a given drive voltage [9], and thus is helpful in countering energy losses incurred in the electrical isolator. The resulting reflections due to the laser impedance mismatch are absorbed by the electrical isolator.

The laser diode output is then coupled (via one of the input ports of a 3-dB optical coupler) to an optical fiber loop formed between the output ports of the directional coupler. The fiber loop contains a 43-GHz bandwidth FFPR, which acts as an optical filter, and a polarization controller. The FFPR can be tuned over its free spectral range (FSR), which was measured to be 38 nm (4750 GHz), by adjusting its tuning voltage (0–10 V). The output from the setup is taken from the other input port of the coupler. This output is then amplified using a Pirelli fiber amplifier, and split in two using a second 3-dB coupler so that the spectral and temporal outputs can be viewed simultaneously. An Anritsu optical spectrum analyzer with a resolution of 0.1 nm was used to view the spectral output, and a 34-GHz photodiode (HP 83440D) with a 50-GHz sampling oscilloscope (HP 54124T) were used to monitor the temporal shape of the output pulse.

Experimental Results

The 500-MHz SRD module was fed with 29 dB (1 mW) of electrical power. The variable attenuator after the electrical isolator was set for 6 dB attenuation. The laser was biased at 4 mA. Part of the optical spectrum from the lone modulated laser is shown in Fig. 2. The mode spacing is 1.5 nm, and the spectral width of the individual modes is around 0.9 nm. The usual spectral shape of the modes due to the chirp [10] can be observed.

The laser output was then coupled to the fiber loop. The pulse repetition rate must be adjusted about 500 MHz to a multiple of the inverse of the light round trip time in the fiber, and the FFPR must be tuned to one of the modes from the Fabry–Perot laser. The polarization controller was adjusted until a maximum amplitude of the output optical pulse was obtained and/or until a minimum time-bandwidth product was obtained. The resulting output responses, temporal and spectral, are shown in Figs. 3 and 4, respectively. The frequency of the source was tuned to 500.988 MHz. The measured output pulse width on the oscilloscope is 17.6 ps. An overall response time of 15 ps is assumed for the combination of the photodiode and the oscilloscope, thus deconvolving gives an actual optical pulse width of 9.2 ps. The spectral output has a width of 0.35 nm, which equates to 44 GHz. Thus the time–bandwidth product of the output pulse is 0.4. This is lower than the transform limit for Gaussian pulses (0.44), but higher than that for hyperbolic secant pulses (0.31). By varying the tuning voltage of the FFPR it was possible to select individual modes from the FP laser and so change the wavelength of the output pulses. The very large FSR of the FFPR (38 nm) ensures that only one mode from the FP laser passes through the filter. The temporal and spectral outputs have the same form at the different wavelengths, although at the extremities of the range of tunability the pulse jitter is increased. The output wavelength is discretely tunable at intervals of 1.5 nm, the mode spacing for the FP laser diode. It was possible to tune the output, near transform-limited optical pulses over a range of around 15 nm.

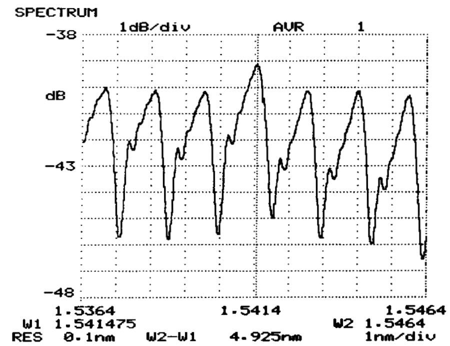

Fig. 2. Part of optical spectrum from gain-switched FP laser (without feedback loop). This shows the characteristic spectral shape of the modes due to chirp.

The spectral output contains kinks at intervals of approximately 0.065 nm (16.25 GHz), which is thought to be due to a reflection in the FFPR.

The FP laser becomes locked into operation at one mode by a form of self-injection locking. The pulse repetition rate must be adjusted to a multiple of the inverse of the light round trip time in the fiber. This is to ensure that the optical pulse being fed back arrives at the same time as an electrical pulse to the laser (within an accuracy of 30% of the width of the optical pulse). Usually at the onset of laser oscillation there is competition between the modes that could be sustained in the cavity, but with single-mode light being injected back into the diode, oscil-

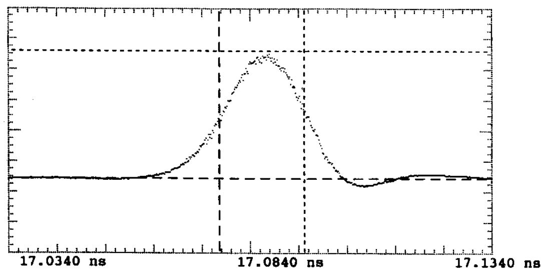

Fig. 3. Temporal response from self-injection locking setup. Measured pulse width is 17.6 ps.

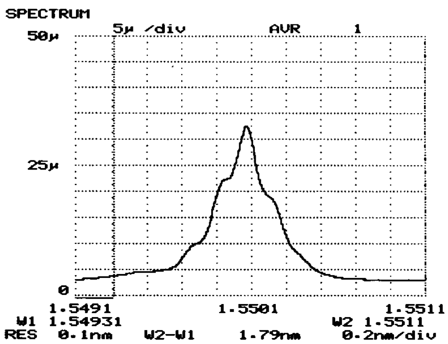

Fig. 4. Spectral output from self-injection locking setup. The kinks in the spectral form every 16 GHz are clearly visible. The spectral width is 0.35 nm.

lation will be at the injected mode. As this occurs the gain of other modes sustainable in the FP cavity will be suppressed.

Conclusion

The FFPR has two purposes: to select one of the modes of the FP laser to be fed back to the laser cavity, and to reduce the optical bandwidth of the selected mode sufficiently to produce near transform-limited pulses. Obviously the output pulses are not continuously wavelength tunable, as it is only at the particular wavelengths of the modes of the FP laser diode that an optical output is achieved. However, the output wavelength can be varied by changing the temperature of the laser diode, and a variation of 10 °C is sufficient to cover the wavelength interval between two modes of the FP laser.

Thus in conclusion, near transform-limited pulses, with a time-bandwidth product of 0.4, have been produced by self-injection locking of a gain-switched FP laser diode. This setup is both simple and robust. The output wavelength is tunable over 15 nm by varying the tuning voltage of the optical filter in the fiber feedback loop. It is believed that this system could be used as a wavelength-tunable source of solitons at higher repetition rates by using strong CW modulation of the laser at high frequencies (e.g., 5 GHz).

Acknowledgment

The authors are grateful to C. Kazimerski for the laser diode.

References

[1] Mollenauer *et al.*, "Wavelength division multiplexing with solitons in ultra-long distance transmission using lumped amplifiers," *J. Lightwave Technol.*, vol. 9, pp. 362–367, 1991.

[2] Iannone *et al.*, "Robust electrically tunable 1.5 μm mode-locked fibre external-cavity laser," *Appl. Phys. Lett.*, vol. 61, pp. 1496–1498, 1992.

[3] Liu *et al.*, "Method of generating nearly transform-limited pulses from gain switched distributed-feedback laser diodes and its application to soliton transmission," *Opt. Lett.*, vol. 17, pp. 64–66, 1992.

[4] Cavelier *et al.*, "Picosecond (< 2.5 ps) wavelength tunable ($\approx$ 20 nm) semiconductor laser pulses with repetition rates up to 12 GHz," *Electron. Lett.*, vol. 28, pp. 224–226, 1992.

[5] J. Stone and L. W. Stulz, "Pigtailed high-finesse tunable fibre Fabry–Perot interferometers with large, medium, and small free spectral ranges," *Electron. Lett.*, vol. 23, pp. 781–783, 1987.

[6] T. Kanada and K. Nawata, "Injection laser characteristics due to reflected optical power," *IEEE J. Quantum Electron.*, vol. 14, pp. 559–565, 1979.

[7] D. B. Mortimore, "Fiber loop reflectors," *J. Lightwave Technol.*, vol. 6, pp. 1217–1224, 1988.

[8] N. Finlayson *et al.*, "Switch inversion and polarization sensitivity of the nonlinear optical loop mirror," *Opt. Lett.*, vol. 17, pp. 112–114, 1992.

[9] Guignard *et al.*, "40 Gbit/s optical network using collision free time division multiplex access," in *Proc. 18th Euro. Conf. Opt. Commun.*, 1992, vol. 1, pp. 613–616.

[10] B. W. Hakki, "Evaluation of transmission characteristics of chirped DFB lasers in dispersive optical fibre," *J. Lightwave Technol.*, vol. 10, pp. 964–970, 1992.