

# Nanosecond Channel-Switching Exact Optical Frequency Synthesizer Using an Optical Injection Phase-Locked Loop (OIPLL)

Cyril C. Renaud, Michael Düser, *Member, IEEE*, Claudio F. C. Silva, B. Puttnam, T. Lovell, Polina Bayvel, *Senior Member, IEEE*, and Alwyn J. Seeds, *Fellow, IEEE*

**Abstract**—Experimental results are reported on an optical frequency synthesizer for use in dynamic dense wavelength-division-multiplexing networks, based on a tuneable laser in an optical injection phase-locked loop for rapid wavelength locking. The source combines high stability (<1-kHz channel frequency error over 5-K temperature change), with high output power (~2 dBm), wide tuning range (40 nm), high spurious suppression (>50 dB), narrow linewidth (10 MHz), and fast wavelength switching (<10 ns).

**Index Terms**—Optical frequency comb generator (OFCG), optical injection phase-locked loop (OIPLL), optical networks, tuneable laser.

## I. INTRODUCTION

DYNAMIC wavelength-routing has been proposed for optical burst- and packet-switched networks [1], [2], as well as for optical switching matrices using passive routers [3]. Such applications require fast tuneable optical transmitters capable of switching between channels in microsecond to nanosecond timescales to enable dynamic lightpath assignment in response to variable traffic demands. The usable wavelength address space and spectral efficiency in these systems can be increased by reducing the channel spacing below the 50-GHz ITU-grid standard, requiring high wavelength stability. Wavelength drift in semiconductor lasers occurs as a result of temperature change (~20 GHz/K), current fluctuation (~1 GHz/mA), or aging mechanisms (~2 GHz/year) [3]. Commercially available etalon-based wavelength lockers could be used to compensate such impairments, but are limited to guard bands of <3 GHz and minimum channel spacings of 25 GHz [4]. The switching times of fiber-based etalon stabilisers are restricted to millisecond timescales (2 ms) [5], not compatible with the requirements of optical packet- and burst-switched networks operating on the microsecond to nanosecond timescale. Recently, locked widely tuneable lasers have reached switching speeds of 50 ns (channel spacing of 100 GHz), with a frequency error <8 GHz [6].

In this letter, we report experimental results for a novel rapid channel-switching dense wavelength-division-multiplexing (DWDM) synthesizer system whose channel frequency is

Manuscript received October 7, 2003; revised November 6, 2003. This work was supported by UK EPSRC, Marconi plc, and the Royal Society.

The authors are with the Department of Electronic and Electrical Engineering, University College London (UCL), London WC1E 7JE, U.K. (e-mail: a.seeds@ee.ucl.ac.uk).

Digital Object Identifier 10.1109/LPT.2004.823724

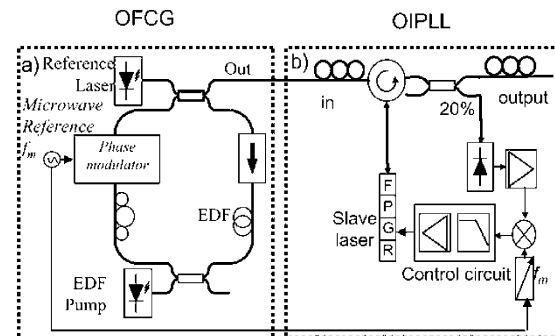


Fig. 1. Experimental system of (a) OFCG and (b) OIPLL.

determined by the supplied optical and microwave reference frequencies [7], combining the advantages of a highly stable and widely tuneable system with fast wavelength switching. By using an atomic transition-locked optical reference, each channel can have an absolute frequency error <20 kHz [8], while the channel frequency spacing is determined by the stability of the microwave reference. We show that the system can hop between specified wavelengths despite 5-K laser submount temperature changes, the widest temperature range for an absolute frequency locking scheme yet reported. We also demonstrate the use of the scheme as a highly stable wavelength source suitable for rapid switching in dynamic ultradense (<25-GHz channel spacing) wavelength-division-multiplexing (WDM) networks and switch fabrics, with electrical pulse generator limited total switching time <10 ns.

## II. EXPERIMENTAL SYSTEM

Fig. 1 shows the experimental system used for the switching experiment. The optical frequency comb generator (OFCG) uses an amplified fiber loop with an embedded phase modulator. The loop, operated as a resonant cavity, multiplies the number of equally spaced side-frequencies produced by the phase modulator, driven by a microwave synthesizer ( $f_m = 18$  GHz) and generates over 100 comb lines after recirculation [7]. The referenced comb spectrum was delivered to a number of channel (slave) lasers in optical injection phase-locked loop (OIPLL) blocks, which were locked to selected lines. This is particularly useful where a number of tuneable lasers need to share a common reference, e.g., in the edge routers of optical-burst switched networks [2].

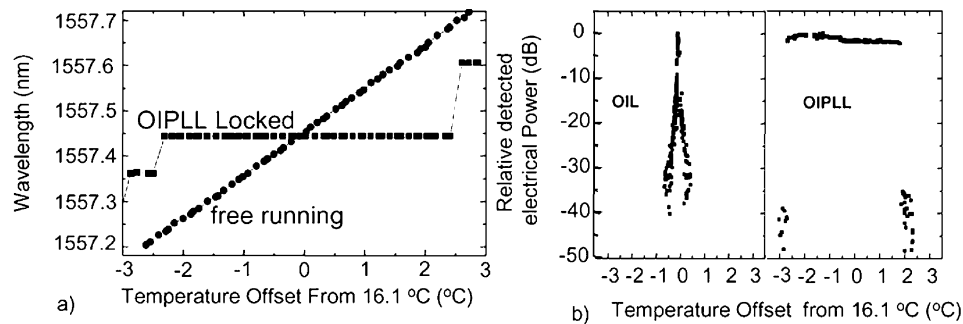


Fig. 2. (a) Wavelength locking as a function of chip temperature measured by FPI. (b) Power of microwave signal generated in 1-kHz resolution bandwidth by beating two OIPLL (or OIL) locked laser diodes (locked on two adjacent lines; 18-GHz spacing).

In the OIPLL technique [9], fast and slow channel laser drifts were compensated by the operation of the optical injection locking (OIL) and the optical phase-locked loop (OPLL) paths respectively, the two locking techniques in combination allowed increased OPLL loop delay time (27 ns), wide channel laser linewidths ( $>10$  MHz), and wide locking ranges simultaneously, in contrast to previously implemented stand-alone techniques [10], which only provided 2-GHz locking range compared with the 80 GHz of the OIPLL technique. Both sample grating distributed Bragg reflector (SG-DBR) and super structure grating (SSG)-DBR lasers were used as slave lasers with similar results.

Wavelength monitoring was carried out using a preselecting optical bandpass filter followed by an all-fiber scanning Fabry-Pérot interferometer (FPI) tuned by a high-precision (1-mV resolution) digital-to-analogue converter, with the FPI output detected using a photodiode and digital storage oscilloscope. An oscilloscope trace was recorded for each voltage/wavelength setting before tuning the FPI by 1 pm ( $\sim 125$  MHz). Scanning the interferometer as the transmitter is, repetitively, switched between wavelengths allows profiles of wavelength and output power against time to be plotted. The wavelength range scanned was  $<1$  nm, limited by the bandwidth of the optical filter.

### III. RESULTS AND DISCUSSION

#### A. Locking Range

Fig. 2(a) shows the locking characteristics measured using an FPI as the laser submount temperature is varied. Note that for this experiment, the loop control voltage was applied to the gain section only [Fig. 1(b)] since this allowed a tuning range of 80 GHz as compared to 40 GHz for the phase section, and this will allow bigger temperature drift, which can be produced by a large current pulse on the grating section. It could, however, induce change of up to 20% in the output power. The OIPLL-controlled laser remained locked (measurement precision is 1 GHz) over a 5-K temperature range.

To provide a higher resolution measurement, we used two OIPLL circuits locked to two adjacent lines from the comb generator spaced 18 GHz apart. By heterodyning the output from the two lasers in a high-speed photodetector and analyzing the resultant signal with an electrical spectrum analyzer, we could measure the frequency difference between the two channel outputs. The coherence of the system leads to a heterodyne signal

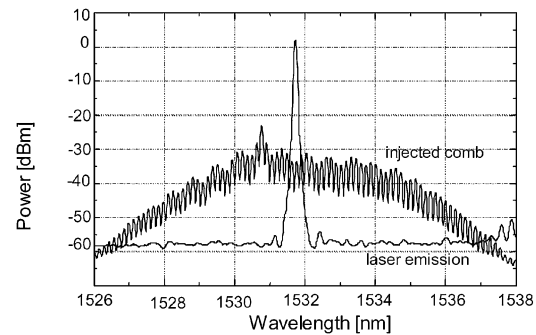


Fig. 3. Optical spectrum of injected comb and locked laser output (0.1-nm OSA resolution).

with low phase noise ( $-75$  dBc/Hz at 10-kHz offset), enabling a narrow spectrum analyzer resolution bandwidth to be used (1 kHz). Fig. 2(b) shows the measured power of the signal with the spectrum analyzer span set to zero at 18-GHz center frequency, while tuning the temperature of one of the lasers. A small temperature change is enough to make the OIL system lose lock, whereas, the OIPLL maintains the 18-GHz frequency difference over a 5-K temperature range.

#### B. Spurious Suppression Ratio (SSR)

High SSR and low linewidths are prerequisites for low crosstalk values when reducing the channel spacing in ultra-dense WDM systems. Fig. 3 shows the spectrum of the locked SG-DBR laser output. The SSR is greater than 50 dB over the 12-nm measurement scan. One of the advantages of the scheme is that the linewidth of the slave laser is equal to that of the master comb line  $<10$  MHz. The output power of the laser, however, solely depends on the slave laser and was measured to be  $>1.7$  dBm at the system output for the SG-DBR laser used in the experiment. Therefore, this source is suitable for DWDM systems with 18-GHz channel spacing (the OFCG channel spacing) over a wavelength range of  $>12$  nm (OFCG limited).

#### C. Switching Speed

Fig. 4 shows the result for switching between 1570 (0 mA on the grating section) and 1529.88 (peak tuning current applied to one grating section: 25 mA) at a frequency of 500 Hz (dwell time on each wavelength 1 ms). The measurement was performed with and without the phase-locked loop to see if, as expected, the locking is limited by the OIL [8]. One can also note that to assess the stability of the locking, the Fabry-Pérot

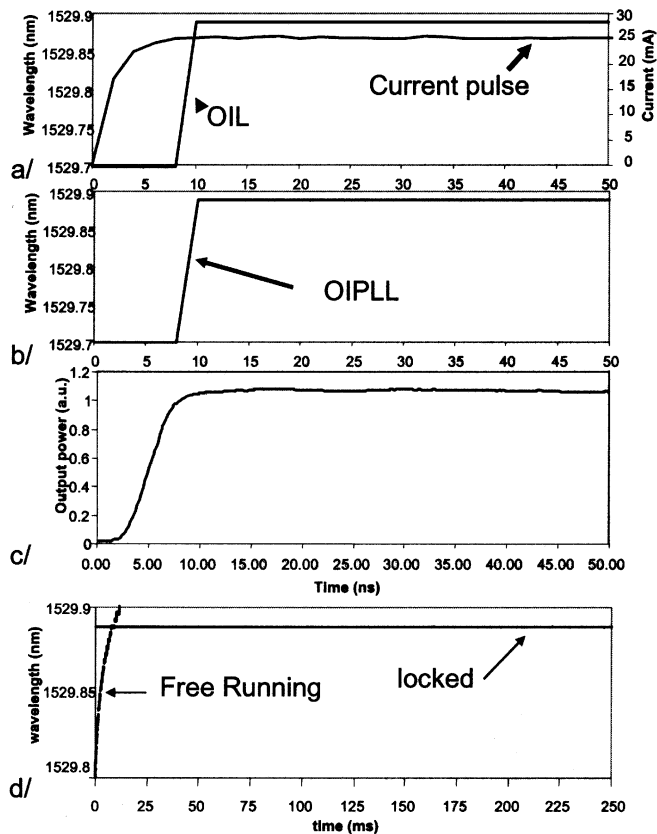


Fig. 4. Channel-switching transient 1570–1532 nm (resolution 1 pm): wavelength stabilization is achieved within 10 ns of the onset of the electrical trigger signal (a) with OIL only and (b) with OIPLL, (c) while the optical output power stabilizes within 10 ns. (d) The OIPLL removes any wavelength drift over 250 ms.

was only scanned between 1529.7 and 1529.9 nm. The new wavelength was acquired to the system measurement accuracy of  $<250$  MHz, within  $<10$  ns, whether the locking is provided by OIL only or OIPLL (Fig. 4(a) is for OIL only), limited by the speed of the laser current controller (8-ns rise time). This confirms that, as expected, the locking is almost instantaneous and limited by OIL locking bandwidth [8] as the acquisition time is the same whether the PLL path is used or not.

The optical output power stabilized within 10 ns of the initial trigger signal (Fig. 4(c), the initial trigger signal; Fig. 4(a), is corrected for the length of the cables to the oscilloscope and the laser diode). This also shows that there is no noticeable temperature drift induced by the current pulse, thus, the loop control voltage could have been applied on the phase section to reduce the output power variations. There was no measurable long-term drift ( $<250$  MHz) for burst lengths up to 250 ms [Fig. 4(d)]. For burst lengths of 50-ms wavelength drift in excess of 0.1 nm (12.5 GHz) was observed for free running operation, which cannot be tolerated in ultradense WDM systems with channel spacings  $<25$  GHz.

#### IV. SUMMARY AND CONCLUSION

All fiber-based OIPLL circuits were used with widely tuneable SSG-DBR and SG-DBR lasers in a first demonstration of a

rapidly tuneable source for dynamic switching in DWDM networks and switch fabrics. Laser controller limited wavelength switching times of  $<10$  ns were obtained, with long-term drift  $<250$  MHz (measurement limit). In high resolution static measurements, we have shown that channel frequency errors remained below the measurement limit of 1 kHz while the laser chips were temperature tuned by 5 K. Further improvement in the hold-in range is possible by applying control signals to the reflector sections, ensuring mode stability. However, the achieved range is sufficient to compensate for thermal and aging frequency drifts over the lifetime of the device, enabling the design of high spectral efficiency channel-switching DWDM systems without guard bands, and with high SSR and low linewidth.

While the total time to acquire lock measured from the trigger pulse was 10 ns, the time to acquire lock once the correct grating section current is reached is less than  $\sim 2$  ns, close to the value expected from OIL theory [9].

The locking technique described here is expected to find application in burst- and packet-routed DWDM networks and wavelength-routed optical switch fabrics.

#### REFERENCES

- [1] M. Düser and P. Bayvel, "Analysis of a dynamically wavelength-routed optical network architectures," *J. Lightwave Technol.*, vol. 20, pp. 574–585, Apr. 2002.
- [2] J. Gripp, M. Duell, J. Simsarian, S. Chandrasekhar, P. Bernasconi, A. Bhardwaj, Y. Su, K. Sherman, L. Buhl, E. Laskowski, M. Cappuzzo, L. Stulz, M. Zirngibl, O. Laznicka, T. Link, R. Seitz, P. Mayer, and M. Berger, "Demonstration of a 1.2 Tb/s optical packet switch fabric [ $32 \times 40$  Gb/s] based on 40 Gb/s burst-mode clock-data-recovery, fast tunable lasers, and a high-performance  $N \times N$  AWG," in *Proc. 27th Eur. Conf. Optical Communications (ECOC 2001)*, Amsterdam, The Netherlands, 2001, Postdeadline Paper PD.A.1.7, pp. 58–59.
- [3] O. A. Lavrova and D. J. Blumenthal, "Accelerated aging studies of multi-section tunable GCSR lasers for dense WDM applications," *J. Lightwave Technol.*, vol. 18, pp. 2196–2199, Dec. 2000.
- [4] D. Le-Guen, S. Lobo, F. Merlaud, L. Billes, and T. Georges, "25 GHz spacing DWDM soliton transmission over 2000 km of SMF with 25 dB/span," in *Proc. 27th Eur. Conf. Optical Communications (ECOC 2001)*, vol. 3, Amsterdam, The Netherlands, Oct. 2001, Paper We.F.1.5, pp. 244–245.
- [5] D. Sadot and E. Boimovich, "Tunable optical filters for dense DWDM networks," *IEEE Commun. Mag.*, vol. 36, pp. 50–55, Dec. 1998.
- [6] A. Dantcha, L. P. Barry, J. Murphy, J. Dunne, T. Mullane, and D. McDonald, "BER performance in wavelength packet switched WDM systems during Nano-second wavelength switching events," in *Proc. 29th Eur. Conf. Optical Communications (ECOC 2003)*, vol. 3, Amsterdam, The Netherlands, Sept. 2003, Paper We4.P.146, pp. 848–849.
- [7] C. F. C. Silva and A. J. Seeds, "Terahertz span  $> 60$ -Channel exact frequency dense WDM source using comb generation and SG-DBR injection-locked laser filtering," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 370–372, Apr. 2001.
- [8] C. R. Schwarze and J. H. Rentz, "Frequency stabilized distributed feedback laser diode system at  $1.323 \mu\text{m}$  using the modulated Zeeman effect," *Rev. Sci. Instrum.*, vol. 70, pp. 3828–3831, 1999.
- [9] C. Bordonalli, C. Walton, and A. J. Seeds, "High-performance phase locking of wide linewidth semiconductor lasers by combined use of optical injection locking and optical phase-lock loop," *J. Lightwave Technol.*, vol. 17, pp. 328–342, Feb. 1999.
- [10] L. A. Johansson and A. J. Seeds, "Millimeter-wave modulated optical signal generation with high spectral purity and wide-locking bandwidth using a fiber-integrated optical injection phase-lock loop," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 690–692, June 2000.