Offset locking of an SG-DBR to an InGaAsP/InP mode-locked laser

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***Abstract*—We demonstrate a Sampled Grating-Distributed Bragg Reflector (SG-DBR) laser offset locked at 6.5 GHz from a diode mode-locked laser comb using an integrated optical phase-locked loop (OPLL).**

Keywords-coherent; optical frequency synthesis; optical phase-locked loop; wavelength stablization.

Recently, highly-integrated optical phase-locked loops (OPLLs) have been demonstrated with 200-300 MHz loop bandwidths [1,2]. These OPLLs allow a tunable slave laser to clone the phase noise of any reference laser within their operating bandwidth. By offset locking an OPLL laser to a stable optical frequency comb, new applications emerge including: digitally synthesized optical frequency sweeps [3] for LIDAR, and THz frequency generation on an optical carrier [4].

In previous work, researchers have used OPLLs to lock two DBR lasers to an optical frequency comb, generating a high spectral purity 300 GHz tone [4]. This comb was generated using phase modulators and a narrow linewidth laser, yet the comb bandwidth was limited to 300 GHz. For many applications broader comb generation is needed, and integration with the OPLL laser improves stability and provides a more compact system. Frequency modulated (FM) InGaAsP/InP lasers have been used for comb generation >1 THz and as references for optical phase-locked loops, however the FM lasers typically suffer from nonuniform spectral power making frequency sweeps difficult [5]. Mode-locked lasers (MLLs) are another promising source for broadband comb generation, and flat bandwidths over 2 THz from a 30 GHz repetition rate monolithically integrated device have been demonstrated, as shown in Fig. 1 [6]. For this reason, many researchers are interested in combining broadband MLLs with OPLLs [4]. Towards this aim, we demonstrate the first offset locking of an SG-DBR laser to a diode MLL on an InGaAsP/InP platform.

For this demonstration, we use a MLL with a smaller repetition rate (18 GHz) and a much narrower spectral bandwidth than shown in Fig. 1. This choice of references allows us to observe the beat frequency between the locked OPLL laser and adjacent comb lines. The mode-locked laser is a ring cavity with length 4400 μm and more details of the fabrication and testing of this laser are described in [7]. Both SG-DBR and MLL are unpackaged and placed on separate carriers and thermo-electric coolers. The MLL is operated at 106 mA drive current to the semiconductor optical amplifiers (SOAs) and -2 V reverse bias on the saturable absorber (SA).

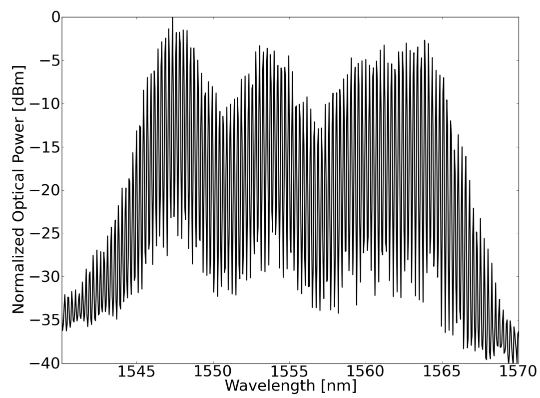

Fig. 1. Optical spectrum of a previously demonstrated InGaAsP/InP 30 GHz repetition rate MLL operating at 250mA drive current and -2.6 V reverse bias on the saturable absorber. Comb extends from 1545 to 1565nm.

The output from the MLL is captured with a lensed fiber and goes through an erbium doped fiber amplifier (EDFA), a 300 GHz optical band-pass filter to reduce the ASE noise from the EDFA, and into the SG-DBR OPLL photonic integrated circuit (PIC), shown in Fig. 2. In the OPLL PIC, the SG-DBR and MLL inputs are mixed using a star-coupler based 90 degree hybrid and detected. The electrical outputs from the detectors are wire-bonded to an EIC, mounted adjacent. The details about the EIC are discussed elsewhere [8]. The EIC feedback signal goes through an active loop filter and back to the phase modulator pad on the SG-DBR.

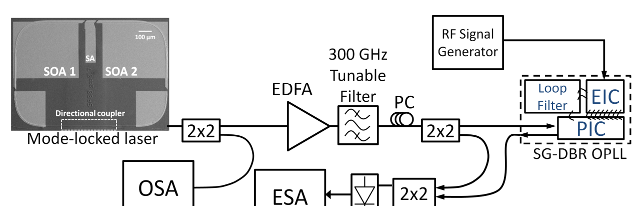

Fig. 2. Test set-up for offset locking the SG-DBR OPLL to the mode-locked laser. The MLL is shown in the top left. Semiconductor optical amplifier (SOA). Saturable absorber (SA). Erbium fiber doped amplifier (EDFA). Polarization controller (PC). Optical signal analzyer (OSA). Electrical spectrum analyzer (ESA).

The power requirement per optical line for stable offset locking is ~4 dBm in the fiber near 1550 nm operating wavelength. As the MLL output is only -10 dBm in the fiber and divided over several comb lines, the EDFA is necessary to provide adequate power levels. However, the ASE noise from the EDFA increases the DC photocurrent on the OPLL PIC and thereby reduces the AC saturation current, making correct operation of the EIC difficult. The tunable band pass filter removes this unwanted noise from the EDFA output. Monolithic integration of the SG-DBR and MLL on a single chip can avoid facet-to-fiber coupling losses and provide adequate power levels without the need for external gain.

To measure the OPLL tone, the output from the SG-DBR is mixed with the MLL in a 2x2 coupler, detected, and measured on an electrical signal analyzer (ESA), as shown in Fig. 3. Offset locking of the SG-DBR is demonstrated at exactly 6.5 GHz and remains locked for the duration of the test (>10 mins). The free-running MLL has a broad optical linewidth >100 MHz, which extends beyond the bandwidth of the loop filter below its peak amplitude. The -20 dB OPLL beat linewidth is ~800 kHz, and a significant widening in the noise pedestal is observed at 25 dB below the OPLL peak. There is a fiber length mismatch of 10m between the reference and OPLL laser paths, which is responsible for the interference fringes at ±20 and ±40 MHz from 6.5 GHz. Thus, the PIC laser is delayed 50 ns relative to the reference signal before mixing, and the reference laser frequency noise broadens the observed beat signal. Therefore, the actual beat linewidth is likely better than we observe. In future work, matched paths will be used.

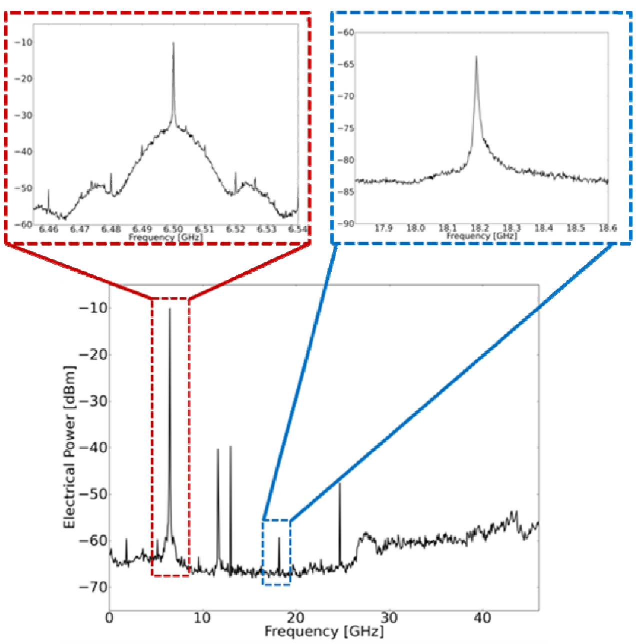

Fig. 3. Frequency spectrum of SG-DBR beating with the MLL measured on an electrical spectrum analyzer (RBW 50 kHz). The offset locking frequency is 6.5 GHz (upper left window, RBW 50 kHz), the second hardmonic of it is visible at 13 GHz. The frequency beating between the SG-DBR OPLL and adjacent comb lines is visible at 11.69 GHz and 24.69 GHz. The mode-locked tone is shown at 18.19 GHz (upper right window, RBW 100 kHz).

The second harmonic of the OPLL beat tone is measured at exactly 13 GHz. The MLL beat tone is observed at 18.19 GHz. However, it is only 20 dB above the noise floor due to the optical filter which reduces the amplitude of the other comb lines. The beat tone between the adjacent comb lines and the SG-DBR are shown at 11.69 and 24.69 GHz (i.e. 18.19 ± 6.5 GHz). The -20 dB linewidth of these two beat tones are both 57 MHz, which is roughly the same -20 dB linewidth as the mode-locked tone at 18.19 GHz. This is expected, since MLL comb lines are nearly phase-locked (to the extent of the MLL beat tone shown at 18.19 GHz) and the OPLL is phase-locked to the central comb line, hence the OPLL is nearly phase-locked to the adjacent comb lines (to the extent of the MLL beat tone shown). To confirm that the mode-locked tone at 18.19 GHz is not an artifact of the OPLL, all beat tones (6.5, 11.69, 13, 24.69 GHz) except the MLL tone at 18.19 GHz vanish with the removal of the SG-DBR signal into the ESA.

The first demonstration of offset locking to a diode mode-locked laser has been demonstrated and preliminary results are shown. Improvements to optical linewidth and the stability of the diode mode-locked laser will greatly enhance the locking performance, and in future work both lasers can be monolithically integrated without significant change to the fabrication of the OPLL PIC.

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