

# Coherent power combination of two Master-oscillator-power-amplifier (MOPA) semiconductor lasers using optical phase lock loops

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**Abstract:** Using heterodyne Optical Phase-Locked Loops (OPLLs), two 1W high power 1550 nm master-oscillator-power-amplifier (MOPA) semiconductor lasers operating as current controlled oscillators are phase-locked to a 1 mW reference laser. The signals of the two MOPAs are then coherently combined and their mutual coherence is studied. In each OPLL, the acquisition range is increased to  $\pm 1.1$  GHz with the help of an aided-acquisition circuit. Control of the phase of a single slave MOPA is demonstrated using a RF phase shifter. The differential phase error between two MOPAs locked to the common reference laser is typically 22 degrees.

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Solid state lasers and fiber lasers with high-power, high brightness, diffraction-limited output beams have found applications in industrial, medical and defense applications [1, 2]. Coherently combined, direct semiconductor laser (SCL) diode arrays using optical phase-locked loops (OPLLs) [3] promise output power, electrical efficiency, brightness superior to solid state lasers and fiber lasers. Coherent combining by use of parallel OPLLs offers additional advantages. It enables potentially more efficient and smaller/lighter weight/lower cost high power laser sources, and also offers high speed phase control of a large number of coherent laser emitters. This latter feature may enable electronically controlled optical beam scanning, adaptive focusing and wavefront control [3].

Recently, we have reported on the coherent combining of two commercial DFB lasers phase-locked to a common reference laser [4]. In the present work we report on the extension of these techniques to high power (~1W) Master Oscillator Power Amplifier (MOPA) SCLs phase-locked to a low power reference laser (~1mW). This work utilizes OPLLs in which control currents are injected directly into the DFB section of each MOPA [5-7] to modulate the optical frequency/phase of the MOPA. Under frequency and phase-lock conditions, the cw optical outputs of the two MOPAs are coherently combined and their mutual coherence is studied.

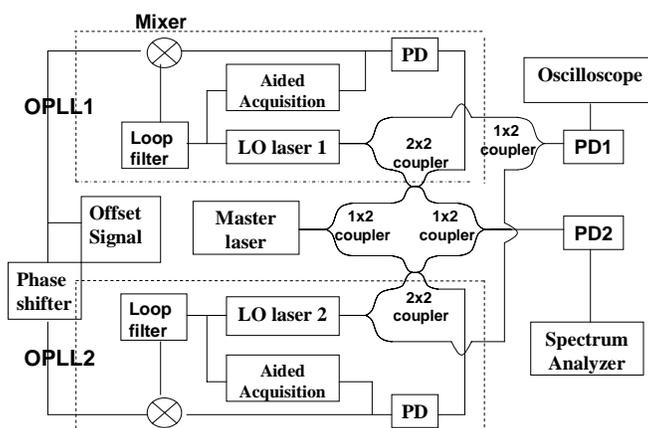


Fig. 1. Schematics of the experimental setup to coherently combine the optical power of two MOPA SCLs local oscillator by phase-locking them, separately to the same low power master laser.

Figure 1 is a schematic diagram of the experimental setup used to demonstrate coherent power combining of MOPA SCLs. Two 1W 1550 nm single mode MOPAs (QPC ES-102) functioning as local oscillators (LOs) are phase-locked to the same master laser using separate heterodyne OPLLs. The 3dB linewidth of the MOPA is measured to be about 0.5MHz using self-delay heterodyne linewidth measurement system. The heterodyne OPLL architecture offers two advantages: First the non-DC base-band beat signal is used to effectively implement an aided acquisition circuit (AAC), which achieves the initial frequency lock upon power-up. Second, the phase of each local oscillator MOPA can be adjusted independently with electronic control by shifting the phase of the RF offset signal distributed to each loop. Each MOPA is further temperature controlled and operated with bias currents for the oscillator section and the amplifier section of 485 mA and 4 A, respectively. The output optical power is ~1 W. The master laser is an Agilent 81640A tunable laser with sub-MHz

linewidth and output power of  $\sim 1$  mW. The frequencies of the LO lasers and the reference laser are offset by the same 1.48 GHz RF signal. In each OPLL, part of the optical power of the MOPA is collected using a flat-cleaved single mode fiber and then combined with the reference optical signal using 2x2 optical fiber couplers. Half of the combined signal is fed to an Archcom AC6536 amplified photodiode (PD). The output beat signal is mixed with the 1.48 GHz offset RF signal generated by a HP 8350A signal generator. The resulted phase error signal is input to a lag-lead filter and the current control signal is injected into the DFB laser section to modulate its optical frequency. The optical power exiting the other port of the 2x2 coupler serves as a monitor output which is fed to a HP 11982A amplified photodiode (PD2 in Fig. 1). By measuring the output signal on a HP 8565E spectrum analyzer, we monitor the locking status of the two OPLLs.

The amplitude and phase of the MOPA-DFB FM response under current modulation of the oscillator section have been characterized using a frequency discriminator and an Agilent 4395A network analyzer [8]. The phase of the current-FM response of each MOPA laser shows less than 30 degrees of variation when measured from DC up to 100 MHz. The FM response does not exhibit the typical sign reversal within the measurement frequency range [9] and enables ideally stable locking over a bandwidth of 100 MHz. By measuring the length of the fiber and the electric path, we estimate that the total loop delay time is  $\sim 8$  ns, which would limit the stable loop bandwidth to about 30 MHz in the absence of electronic delay compensation. We have implemented a lag-lead compensation network with transfer function  $(1+1.4\times 10^{-8}s)/(1+6\times 10^{-8}s)$ . The function of the lag-lead compensation filter is to increase the loop gain at low frequency and thereby increase the acquisition range of the OPLLs to  $\sim 60$  MHz. To further increase the acquisition range an aided acquisition circuit (AAC) is used. The AAC compares the frequency of the optical beat signal with the frequency of the offset RF signal and generates a current ramp which shifts the local oscillator optical frequency and thus the beat signal frequency to within the acquisition range of the OPLL. Detailed designs and functions of the compensation lag-lead network and the AAC will be presented in a conference paper [10]. With the help of these circuits, the acquisition range is improved from  $\pm 9$  MHz to  $\pm 1.1$  GHz.

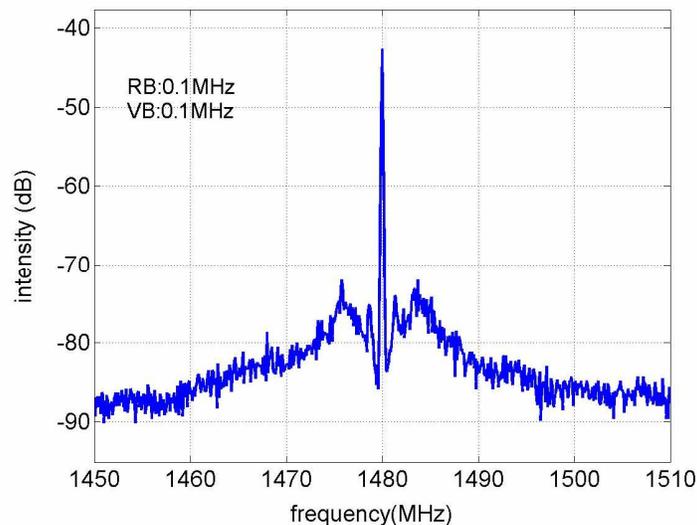


Fig. 2. Measured power spectrum of the locked beat signal.

Figure 2 shows the power spectrum of the locked beat signal of a single OPLL. The central peak reflects the locked beat signal. The bumps at  $\pm 4$  MHz away from the signal reflect the

180 degrees phase shift of the open loop transfer function, which can be attributed to the FM response of the laser, the  $\sim 8\text{ns}$  loop delay, the phase lag of the lag-lead filter and all the other electronics such as the poles of the biasing current source. The noise power can be obtained by integrating the spectral density over the whole frequency range except the central frequency. By calculating the signal to noise ratio, we estimate that the differential phase error between the LO laser and the reference laser is about 18 degrees [11]. Figure 3(a) compares the waveforms at the output of the two PDs in the independent OPLLs when both loops are in lock. The signals shown on Fig. 3(a) are down converted to a few MHz from 1.48GHz due to the limited speed of the oscilloscope. The locked beat signal of the first OPLL (the upper waveform) is used as the trigger signal for the Oscilloscope, and the jittering of the second locked beat signal (the lower waveform) reflects the differential phase error between the two signals. The relative static phase difference is caused by mismatch between the two OPLLs and doesn't vary with time since both signals are locked to the common RF offset signal. As mentioned in the introduction, one of the advantages of the heterodyne OPLL scheme is the ability to control the optical phases of the individual slave MOPAs by shifting the offset RF signal phase at the input to each OPLL by using a RF phase shifter. In Fig. 3(b) the two waveforms are electronically matched in phase using this approach. The extension of this phase programmability to phase-locked diode laser arrays may, in the future, enable high speed beam scanning and adaptive focusing/wavefront correction.

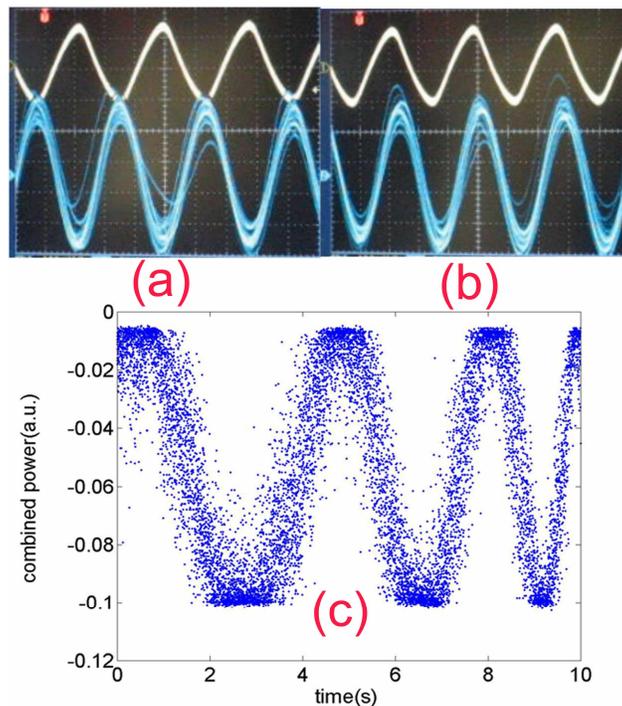


Fig. 3. (a) and (b) Comparison of the time domain waveforms of the output signals of the photo detectors in the two OPLLs. (c) Time domain measurement of the coherently combined power.

After both OPLLs are independently locked to a common optical reference laser, optical signals from the two MOPAs are combined and detected on PD1. Figure 3(c) displays the output of PD1 in the time domain. When both the MOPA SCLs are locked they are offset from the reference laser by the fixed RF frequency and have identical optical frequencies. The optical signals are coherently added and the output of PD1 is, ideally, a DC signal which in our case varies slowly on the time scale of seconds as can be seen on Fig. 3(c). This slow variation results from the change in optical path length along the input paths to the fiber optic

coupler due to slow variation of temperature. From the measured RMS variation of the slowly varying signal, we estimate that the RMS differential phase error between the two combined signals is about 22 degrees.

In conclusion, independent diode lasers can be driven by high speed PLL circuits such that their optical outputs are highly coherent to one another. We have demonstrated that independent, high power amplified DFB lasers can be coherently combined by use of high speed phase-locked loop circuitry. In principle, this approach is scaleable to large, electrically efficient diode laser arrays. The authors wish to acknowledge the support of DARPA's MTO office (J. Mangano, M. Stickley) and T. Salvi of Kirtland Air Force Base.