Optoelectronic Phase-lock Techniques for the Phase and Frequency Control of a Semiconductor Laser

by Amnon Yariv

Almost all of the information-related applications of lasers to date have been based on a manipulation of the amplitude of the laser radiation. This is in sharp contrast to the field of radio-frequency (RF) electronics where the phase of the radio wave plays a key role. Specifically, phase-lock loop (PLL) systems are the main enablers of many applications—wireless communication, CDMA, FM demodulation and clock recovery, to name a few.

The semiconductor laser (SCL) is the transmission source in optical communication networks, and has a number of unique properties, such as its very large current-frequency sensitivity, fast modulation response, small volume and compatibility with electronic circuits. Research in our group has focused on using these unique properties to import to optics and optical communication many of the important applications of RF electronics. This phase control, when combined with the wide bandwidth of optical waves, can enable a new generation of photonic and RF systems. With support from the Lee center, we are studying many novel applications of optoelectronic phase and frequency control. These applications include: distributed low-cost sensor networks; high-power electronically steerable optical beams; arbitrary waveform synthesis; and wideband, precisely-controlled swept-frequency laser sources for 3-D imaging, chemical sensing and spectroscopy.

Optical Phase-lock Loops

Optical phase-lock loops (OPLLs) are negative feedback control systems where a SCL acts as a "slave" oscillator whose phase and frequency are locked to the phase and frequency of a high-quality "master" laser. The main differences between an OPLL and electronic PLLs are the wide linewidth and non-uniform frequency tuning characteristics of typical SCLs as compared to electronic oscillators. We have developed novel phase-locking architectures to overcome these effects and achieve stable phase-locking. When the loop is in lock, the phase coherence of the high quality master laser is transferred to the slave laser. This "coherence cloning" is shown in Figure 1, where the frequency noise of the slave laser is reduced by about two orders of magnitude within the loop bandwidth[1]. The improved coherence enables the replacement of expensive narrow linewidth lasers by inexpensive, compact and efficient coherence-cloned SCLs in long range sensing networks.

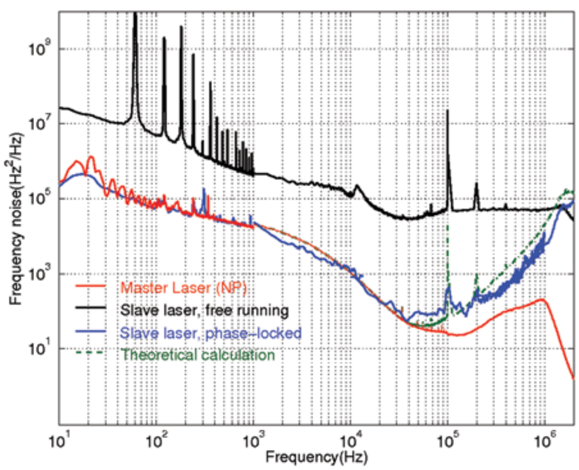

Figure 1: Measured spectrum of the frequency noise of the laser. The frequency noise of the master laser is cloned onto the phase-locked slave laser within the loop bandwidth.

We have also pioneered the application of phase-locked lasers to phase-controlled coherent arrays for power combination and beam steering. Individual SCLs when locked to a common master laser are coherent relative to each other, and their outputs can therefore be coherently combined. The resulting combined output light from such an array of locked lasers gives a higher peak intensity as compared incoherent combination. Further, we have shown that the use of an RF offset in the OPLL permits electronic control over the optical phase on a one-to-one basis, enabling electronic beam steering and adaptive optics at high speeds.

Broadband Swept Frequency Sources for High Resolution Imaging and Spectroscopy

Swept-frequency—or "chirped"—optical sources with large frequency excursions would be useful in high-resolution 3-D imaging applications. For example, applications such as laser radar, biometrics and optical imaging would benefit greatly from such a source since the depth resolution is inversely proportional to the frequency excursion of the source. A state-of-the-art, chirped-laser source consists of an external cavity laser

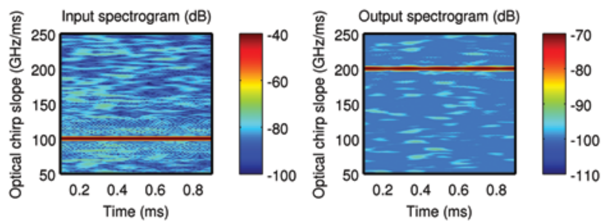

Figure 2: Experimental demonstration of a precisely linear optical frequency chirp using an SCL in an optoelectronic control loop (left) and the doubling of the frequency chirp slope by the process of four wave mixing (right).

whose cavity length, and hence the lasing frequency, is tuned mechanically. The laser is therefore bulky and unreliable; and the tuning speed is limited by the mechanical nature of the tuning mechanism. Further, it is difficult to precisely control the shape of the laser frequency vs. time curve.

We have developed an optoelectronic feedback technique for precise control over the shape of the laser chirp[2], where the chirp is determined by the frequency of an external RF oscillator, and not by the individual laser used in the source. The result is a compact, solid-state laser source with no moving parts that outputs a wideband (>100 GHz), linear frequency chirp vs. time, (see left panel of Figure 2). We have further shown that the slope and bandwidth of the frequency chirp can be doubled by the non-linear optical process of four-wave mixing (FWM)[3], (see right panel of Figure 2). A cascaded implementation of FWM stages can be used to geometrically increase the chirp bandwidth. Moreover, we have demonstrated that a number of chirped SCL sources that chirp over distinct regions of the optical spectrum can be combined to effectively approximate a single wide-bandwidth chirp[4], an approach similar to techniques employed in synthetic aperture radar.

Ongoing and Future Work

With the advent of hybrid III-V/silicon lasers and photonic integrated circuits on silicon and III-V platforms, our future research efforts will focus on the integration of functions (see Figure 3).

Beyond the applications mentioned earlier, we are also exploring use of electronically controlled chirped sources in spectroscopy, and chemical and biological sensing, where the narrow linewidth and precisely controlled frequency of the optical source enables stable, high-resolution frequency measurements. Further, by mixing a chirped laser with another optical wave on a high-speed mixer, these broadband sources can serve as sources in terahertz spectroscopy and imaging.

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Read more at:

http://www.its.caltech.edu/~aphyariv/base.html

References

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[4] A. Vasilyev, N. Satyan, S. Xu, G. Rakuljic, and A. Yariv, "Multiple-source FMCW reflectometry: theory and experiment," *Appl. Opt.*, in press.

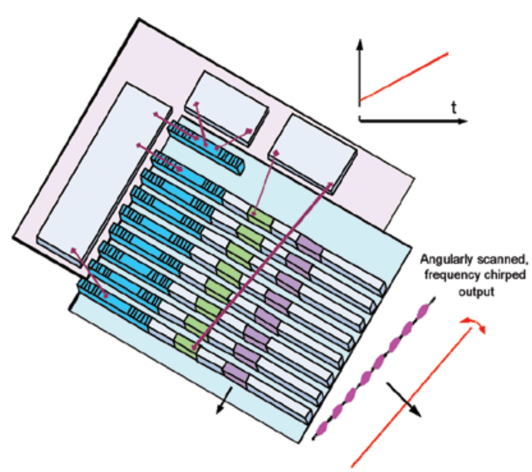

Figure 3: Schematic diagram of an integrated, frequency-chirped coherent optical source.