CW Injection Locking of a Mode-Locked Semiconductor Laser as a Local Oscillator Comb for Channelizing Broad-Band RF Signals

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***Abstract*—CW injection locking of mode-locked semiconductor lasers has been experimentally demonstrated. The phases of the mode-locked frequency comb are shown to be coherent with that of the master CW laser. The pulsewidth of the mode-locked laser remains almost unchanged (<2 ps) for a broad range of injection power (-28 to -12 dBm). Pulling of the entire mode-locked frequency comb by 400 MHz has been demonstrated. The coherent multifrequency source can be used as a local oscillator comb for coherent optical channelizers for ultrawide-band RF signals.**

***Index Terms*— Dense wavelength division multiplexing, external cavity lasers, injection locking, microwave photonics, mode-locked semiconductor lasers, optical channelizer, optical frequency comb generation, RF photonics, semiconductor lasers.**

I. Introduction

Heterodyne communication systems are known for their increased receiver sensitivity and excellent frequency selectivity. In conventional optical heterodyne systems, optical local oscillators (LO) that track the phase of incoming optical carriers are used to demodulate the RF signals. Optical phase-lock loops (OPLL's) [1] and optical injection phase-lock loops (OIPLL's) [2] were used to lock the beat frequency of two semiconductor lasers in the microwave range. Most of the previous work in coherent optical communication has focused on systems with a single local oscillator. Recently, there has been considerable interest in the use of phase-locked optical frequency combs (OFC's) as local oscillators in coherent optical systems. This opens up many new applications such as optical channelization of broad-band RF signals [3] and down-converting of single-channel high-frequency signals [4]. The OFC generated by Bragg cells has been sucessfully applied to acoustooptic (AO) channelizers [3], [5], [6]. The frequency range of Bragg cells, however, is limited to a few gigahertz. Therefore, new phase-locked OFC local oscillators with a frequency span over several tens of gigahertz are of great interest to process ultrawide-band RF signals.

Resonant waveguide modulators have been proposed as compact sources for OFC [7]. The resonance enhances the modulation depth and the extent of the modulation sidebands. The linewidth of the individual frequency in the OFC is as narrow as that of the optical source. The phases of the OFC can be locked to that of another laser by conventional techniques. The drawback of this approach is that the magnitudes of the sidebands drop off very quickly with the harmonic number. Narrow comb spacing also requires a relatively long waveguide. Supercontinuum generation has also been used to generate frequency combs spanning over several terahertz [8], [9]. However, this nonlinear process requires very high optical powers and long lengths of fiber to enhance the nonlinearity. The phases of the individual modes are very sensitive to power fluctuations. Phase locking of the supercontinuum spectrum to a single source is not well studied.

OFC generation using phase modulation in an amplified circulating loop has also been reported [10]. High optical powers and relatively flat comb spectra have been achieved across the entire gain bandwidth of the erbium-doped fiber amplifier (EDFA). The comb frequency needs to be an integral multiple of the mode spacing. Active stabilization of the loop length may be required to achieve a precise comb spacing. An extension of this approach is a mode-locked fiber laser with an electrooptic intensity modulator. Typical cavity lengths of a fiber laser are on the order of 20 m, corresponding to a mode spacing of 10 MHz. Therefore, to generate a comb spacing of 1 GHz requires the suppression of 99 modes between the teeth of the OFC. Typical sidemode suppression is on the order of 40 dB optically [11]. The spurious tones that fall within the IF of a desired channel will limit the dynamic range of the channelizer.

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Mode locking of semiconductor laser has also been studied for OFC generation [12], [13]. Compared with mode-locked fiber lasers, the cavity lengths of mode-locked semiconductor lasers are much shorter and fundamental operation can be achieved at frequencies above 1 GHz. Monolithic mode-locked semiconductor lasers have been demonstrated for frequencies as low as 4.4 GHz [14]. For comb spacing of 1 GHz, external-cavity mode-locked lasers are usually employed.

Optical injection locking has been shown to be a viable technique to stabilize two free-running lasers without using high-speed electronics. This technique offers a large locking bandwidth whereas electronic phase-lock loops are limited by the electrical bandwidth, the linewidth of the lasers used, and the inherent loop delay [15]. The RF phase noise of the beat frequency of two injection-locked CW lasers has been measured to be as low as −125 dBc/Hz at 100 kHz offset [16], which is comparable to high-performance synthesizers. Recently, injection locking of mode-locked semiconductor lasers has spurned new interests in both temporal synchronization and spectral control of mode-locked lasers. Three variations of this injection-locking technique have been reported: 1) a mode-locked master laser injected into a mode-locked slave laser [17]; 2) a mode-locked master laser injected into one or several CW slave lasers [18]; and 3) a CW master laser injected into a mode-locked slave laser [19]–[21].

Variant 1 offers both spectral and temporal control of the mode-locked slave laser [17] and can be viewed as a form of multimode injection locking. Variant 2 offers a new method to phase lock several free-running CW lasers for photonic oscillator applications [18]. Variant 3 is very useful for phase locking the output of the mode-locked laser with a single-frequency master laser. This method can be used to select a particular supermode of a harmonic mode-locked laser [19] and stabilize a passively mode-locked slave laser if the CW master carrier is modulated [20]. Linewidth narrowing of the optical frequency comb has also been observed using this technique [21]. However, the use of CW injection-locked mode-locked laser as a coherent OFC source has not been investigated. In this paper, we report on the successful generation of a coherent OFC using CW injection locking of mode-locked semiconductor lasers. The OFC with 1-GHz comb spacing has been locked to an external CW laser with a total locking range of 800 MHz. Frequency pulling of the OFC by the CW laser has been observed experimentally. Potential application of the phase-locked OFC local oscillator in coherent optical channelizers is discussed.

II. External-Cavity Mode-Locked Semiconductor Laser for Optical Comb Frequency Generation

To generate the desired frequency comb, a hybrid mode-locked external-cavity semiconductor laser with 15-cm-long cavity is constructed to achieve a mode spacing of 1 GHz. [Fig. 1(a)]. A multiquantum-well (MQW) etched-mesa buried heterostructure (EMBH) laser is anti-reflection (AR) coated with a multilayer dielectric coating on the intracavity facet. An aspheric lens is used to couple the output into an external cavity that consists of a plane mirror. Wavelength tuning is achieved using an intracavity etalon with a full-width at half-maximum (FWHM) bandwidth of 5 nm. The EMBH laser is divide into three sections [Fig. 1(b)]. The longest section is used as the gain region and the two small sections near the facets are either reverse-biased as a saturable absorber or modulated with an RF synthesizer. By comparing *L–I* curves before and after the AR coating, the reflectivity is estimated to be less than 1%.

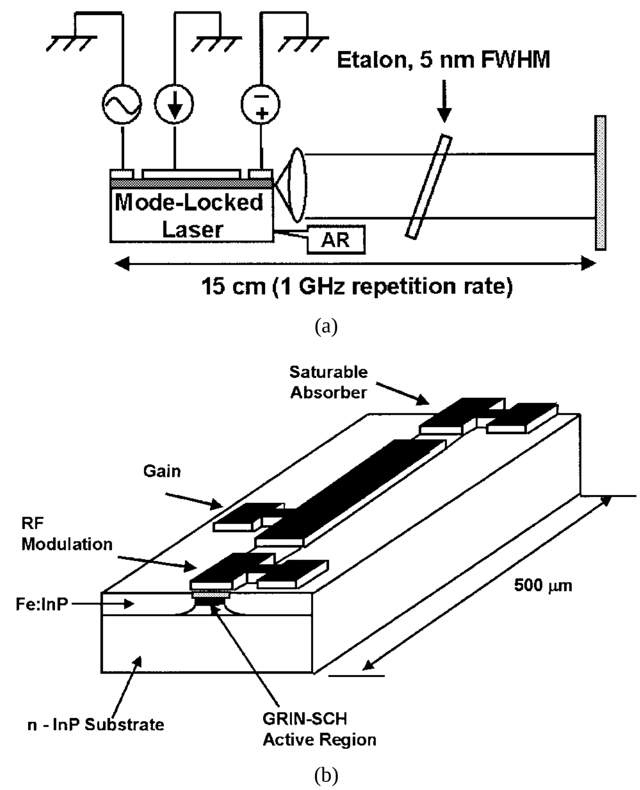
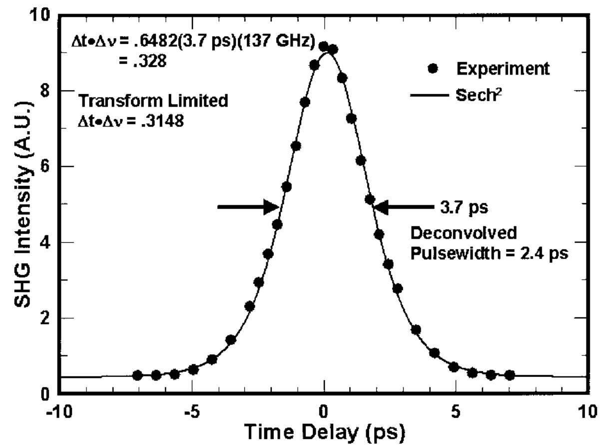


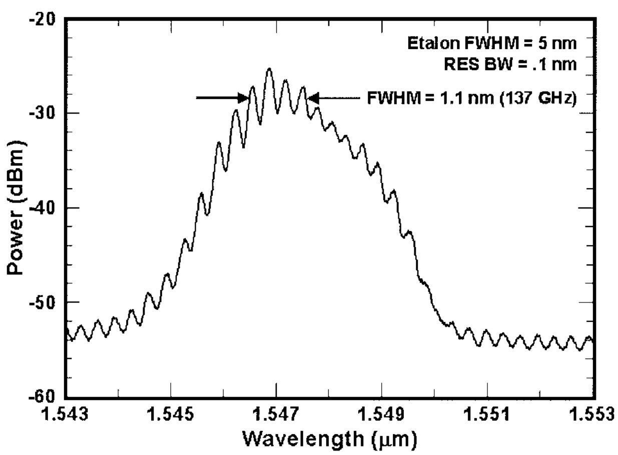
Fig. 1. (a) External-cavity mode-locked laser configuration. (b) EMBH MQW three-section laser.

Typical CW output power in the external-cavity configuration is 1 mW centered at the 1550-nm wavelength. By tuning the angle of the intracavity etalon, the center wavelength can be tuned from 1540 to 1580 nm. The etalon allows wavelength tuning without significant change of the cavity length as opposed to a grating reflector. The etalon limits the bandwidth of the mode-locked semiconductor laser to increase the power per mode, which is important for channelizer applications. A smaller bandwidth also helps prevent incomplete or cluster mode locking [22], [23].

Hybrid mode locking with integrated saturable absorber and loss modulation are employed here [24]–[26]. In a hybrid mode-locked laser, the saturable absorber performs the majority of the pulse-shaping process and the RF modulation is used to provide a timing reference. Passively mode-locked lasers tend to have large timing jitter due to the lack of an external reference. By introducing a small modulation section, the timing jitter can be reduced significantly. Actively mode-locked semiconductor lasers typically require more than 25 dBm of modulation power and produce highly chirped pulses, whereas a relatively low RF power of 5 dBm is adequate in a hybrid mode-locked scheme.



(a)



(b)

Fig. 2. (a) Autocorrelation trace of an external-cavity hybrid mode-locked laser. (b) Optical spectrum of a hybrid mode-locked laser.

III. Mode-Locked Laser: Experimental Results

The output of the hybrid mode-locked external-cavity laser is measured with a noncollinear autocorrelator. Fig. 2(a) shows the autocorrelation trace of the pulses with a deconvolved pulsewidth of 2.4 ps. Neglecting the modulation depth in the optical spectrum, the bandwidth of the pulse is approximately 137 GHz centered at a nominal wavelength of 1550 nm. [Fig. 2(b)] This corresponds to a time–bandwidth product of 0.328, which is very close to the transform limit of 0.3148 for a sech^2 pulseshape [22]. By tuning the intracavity etalon, the center wavelength can be tuned precisely. A tuning range larger than 20 nm has been achieved while maintaining nearly transform-limited pulsewidths of less than 3 ps (Fig. 3).

An imperfect AR coating modulates the gain spectrum by the monolithic mode spacing [Fig. 2(b)], which translates to trailing pulses in the time domain [23]. The imperfect AR coating also increases the likelihood of exciting higher order supermodes which can lead to pulse break-up and longer pulsewidths [23]. These trailing pulses can be eliminated by either perfecting the AR coating, employing angled waveguide structures, or using an intracavity saturable absorber [27].

Typical average mode-locked power is -8 dBm, corresponding to approximately 1 μW per mode. The output power

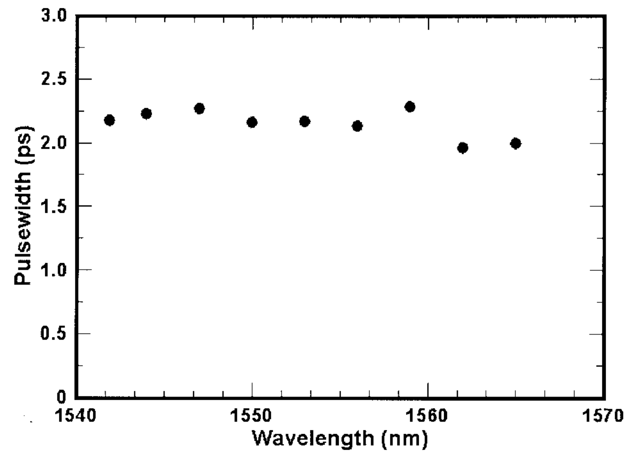


Fig. 3. Pulsewidth at various center wavelengths.

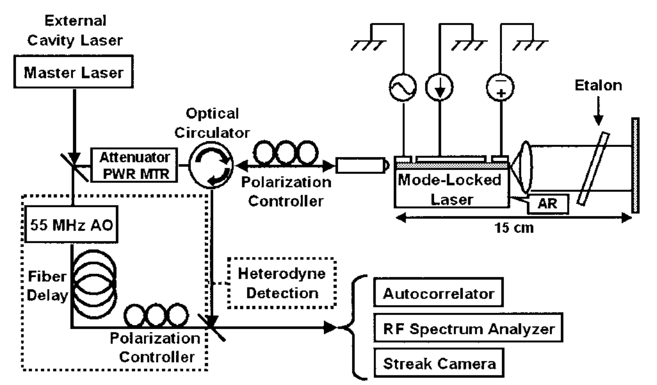


Fig. 4. Experimental setup for injection locking of a mode-locked semiconductor laser.

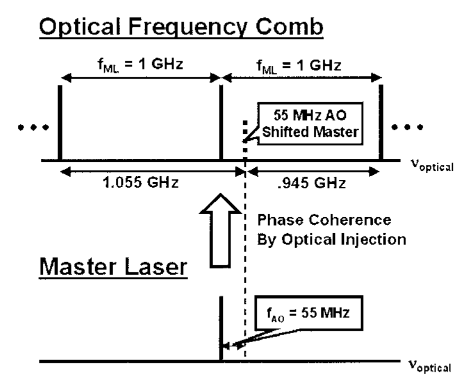


Fig. 5. Heterodyne detection of an injection-locked mode-locked laser.

is limited by the saturation energy of the monolithic saturable absorber, typically on the order of 1 pJ. High optical power per mode is important to achieve the required spur-free dynamic range for channelizer applications. Higher average powers can be obtained by replacing the external mirror with a saturable Bragg reflector (SBR) [28], [29]. The saturable absorber can then be placed in its most effective position, as well as increasing the saturation energy, resulting in higher power per mode and a narrower linewidth. Recent experiments have demonstrated an external-cavity mode-locked semiconductor laser using a SBR with compressed pulsewidths as short as 880 fs [30].

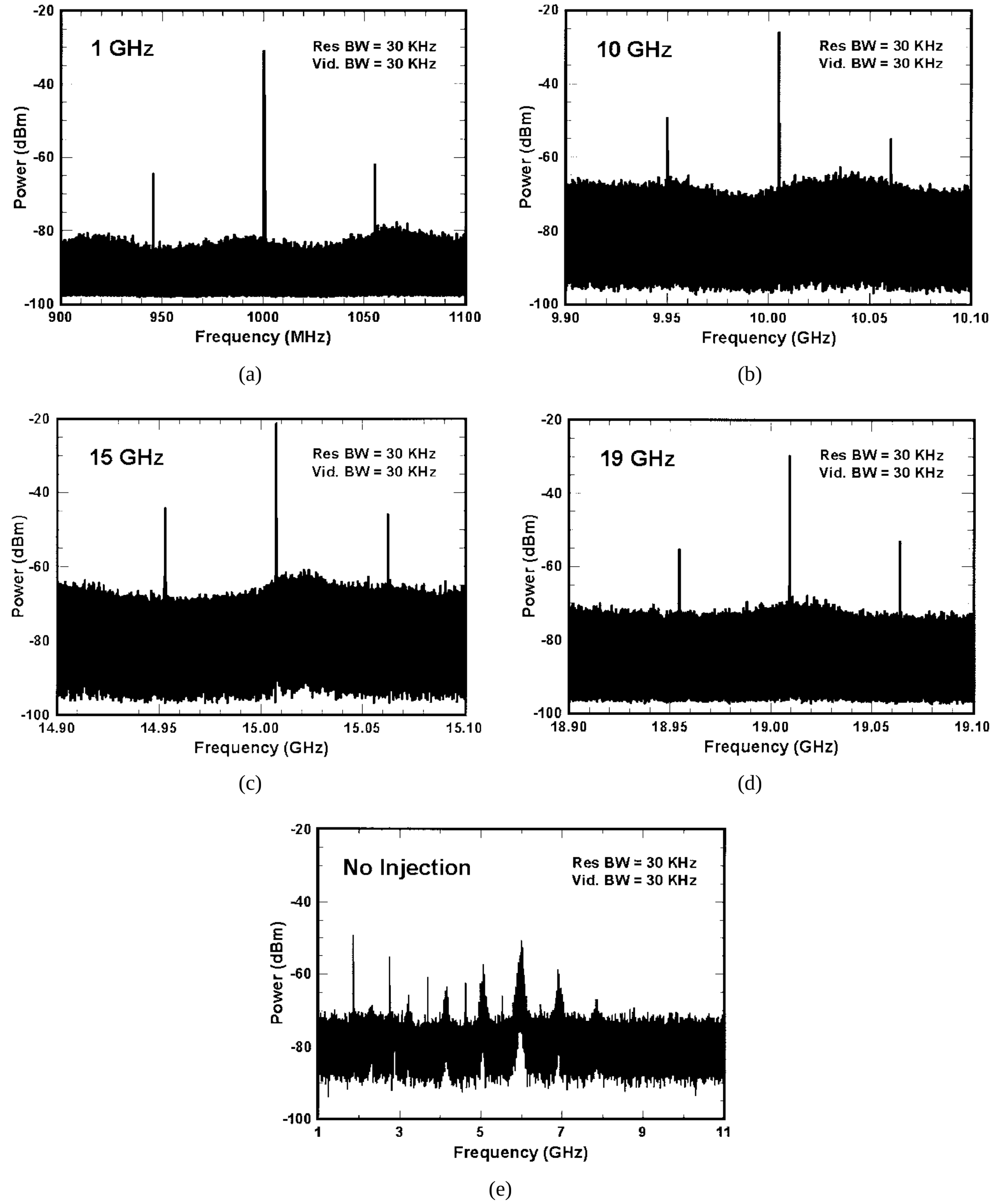


Fig. 6. Heterodyne tones of injection-locked mode-locked laser. (a) Modes 1 GHz away from injected mode. (b) Modes 10 GHz away. (c) Modes 15 GHz away. (d) Modes 19 GHz away. (e) Beat tone of filtered free-running mode-locked slave laser and CW master laser.

Fig. 4 shows a schematic layout of the experimental setup for CW injection locking of the mode-locked slave laser. An external cavity laser is used as the master laser. The output is split with one arm directed to an acoustooptic frequency shifter, and the other arm is attenuated and injected into the mode-locked slave laser via an optical circulator. Polarization controllers are utilized in the injection arm and in the detection arm. A delay line is introduced into the heterodyne arm to minimize the excess phase noise found in heterodyne detection schemes [31].

When the master laser is injected into one of the modes of the slave laser, phase coherence is established between the master and that particular mode, similar to CW optical injection locking. Since in a mode-locked laser all the modes are phase locked, the whole frequency comb is phase coherent with the master laser. The modes of the slave laser can also be pulled from the free running frequency. To detect the phase coherence and the mode-pulling phenomena, the heterodyne detection scheme of Fig. 5 is used.

When detected with a high-speed photodetector and RF spectrum analyzer, harmonics of the mode-locked laser can be seen at multiples of 1 GHz. In addition, tones spaced 55 MHz from the harmonics can be observed, as shown in Fig. 6(a)–(d). These tones are due to the heterodyne of the frequency-shifted master with the modes of the mode-locked laser. In Fig. 6(a)–(d), sidebands at 945 and 1055 MHz indicate that the modes adjacent to the injected mode are phase coherent with the master laser. The sidebands at 9.945 and 10.055 GHz indicate the modes that are 10 GHz away from the injected mode are also phase coherent with the master laser. These tones can be observed up to 19 GHz, indicating that the two modes 19 GHz away from the injected mode are also phase coherent with the master laser. This corresponds to the supermode behavior where the optical spectrum of a mode-locked laser operates as a quasi-single mode [32]–[34]. For comparison, Fig. 6(e) shows the free-running beat tone of a filtered mode 6 GHz apart from the CW master laser. The beat tone is relatively broad, indicating that the lasers are not phase locked. The harmonics of the mode-locked laser are also observed due to the finite finesse of the filter used.

The first parameter of interest is how the pulse characteristics change with injected optical power. When the laser is well mode locked using the hybrid technique, the autocorrelation trace shows 100% modulation depth in the pulses [Fig. 7(a)]. Again, trailing pulses are observed due to the imperfect AR coating. Taking the autocorrelation trace over a full scan of 100 ps shows that there is no slowly varying substructure. The master laser is then tuned to the center wavelength of the mode-locked laser until injection locking is observed on the RF spectrum analyzer. Autocorrelation traces are taken at various injected optical powers. The pulsewidth and pulseshape show little change at low optical injection levels. At injected optical powers comparable to the external average mode-locked power, the balance between gain and saturable absorption is greatly perturbed. This gives rise to a broader pulsewidth and an increase of substructures in the pulse shape [Figs. 7(a)–(c)]. Fig. 8 shows the pulsewidth versus the injected optical power. When the injected optical power is much larger than the average power of the mode-locked laser, the optical injection tends to force the slave laser to operate in the CW mode.

IV. Physics of Injection Locking of Mode-Locked Lasers

Active mode locking is achieved by using a modulator to couple the individual modes of the laser. The modulator modulates the cavity modes at approximately the cavity mode spacing and generates sidebands. These sidebands are coupled into the adjacent cavity modes and create phase coherence throughout the spectrum [35], [36] [Fig. 9(a)]. Similarly, when the master laser is injected into a mode of the slave laser, phase coherence is established with that particular mode. This mode is then modulated to generate sidebands which are phase coherent with the master laser. These sidebands then couple into adjacent modes throughout the spectrum to establish phase coherence between the mode-locked slave laser and the master laser. The evidence of sideband generation can be observed using a high-resolution scanning Fabry–Perot. Fig. 9(b) shows the injected light that is far away from a cavity mode and thus not injection locked. The sidebands generated by the modulation of the injected light are shown and have comparable power due to the inherent gain in the medium.

Similar results have been published in [20], where a double side-band suppressed carrier (DSB-SC) signal is used to stabilize a passively mode-locked distributed Bragg reflector (DBR) laser. The DSB-SC signal will simultaneously inject into two modes of the mode-locked laser and establish phase coherence. Also, the frequency spacing of the DSB-SC signal will pull the slave laser mode spacing and thus alter the repetition rate.

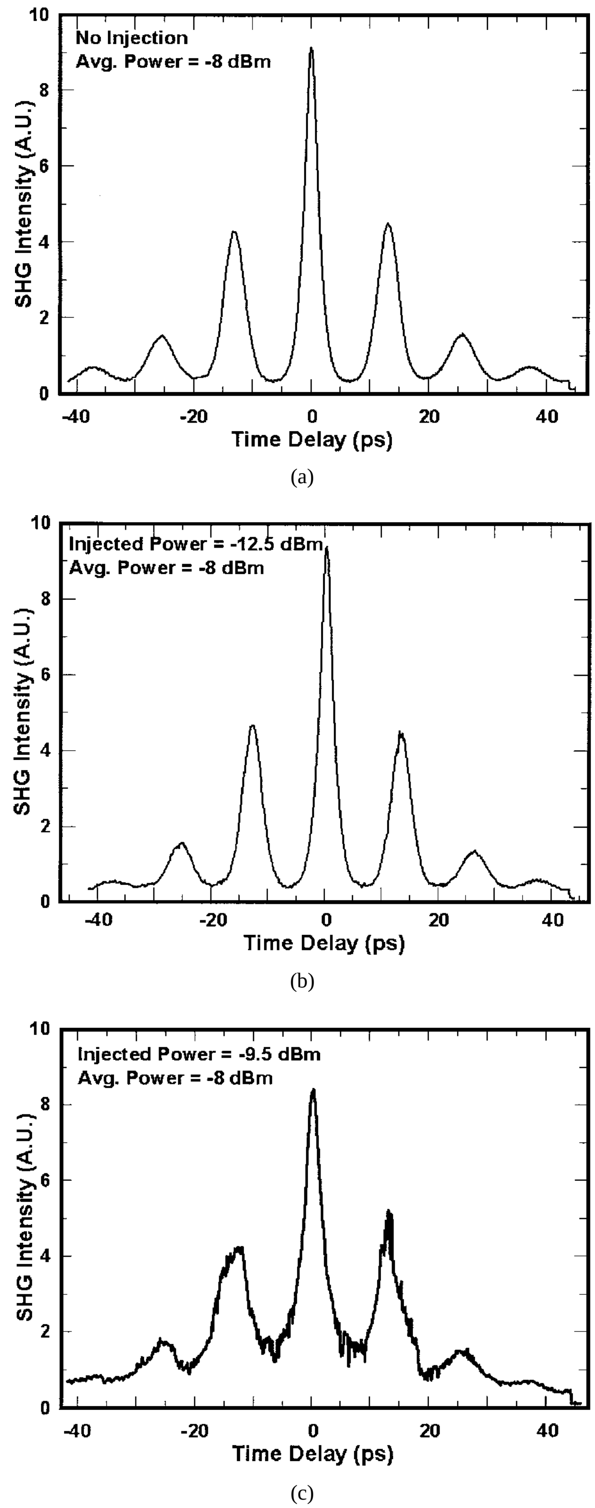


Fig. 7. Autocorrelation trace of a mode-locked laser at various injected optical powers. Autocorrelation trace of mode-locked laser with: (a) no optical injection, (b) −12.5-dBm injected optical power, and (c) −9.5-dBm injected optical power.

Fig. 9(b) shows similar results where the modulation section of the monolithic laser generates side-bands.

The locking bandwidth can be determined by simultaneously tuning the wavelength of the master laser and monitoring the heterodyne tones on the RF spectrum analyzer. The locking bandwidth is defined as the tuning range such that injection

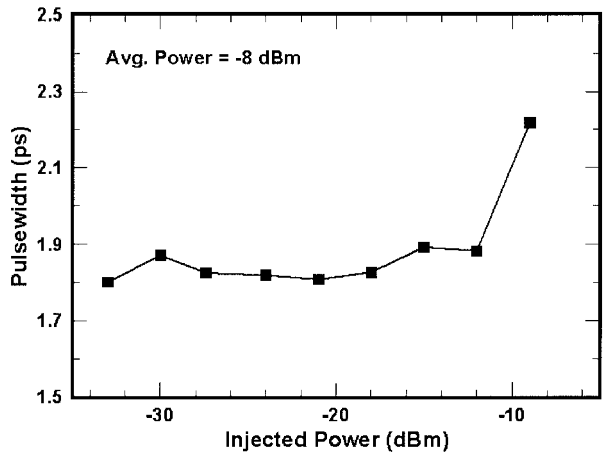
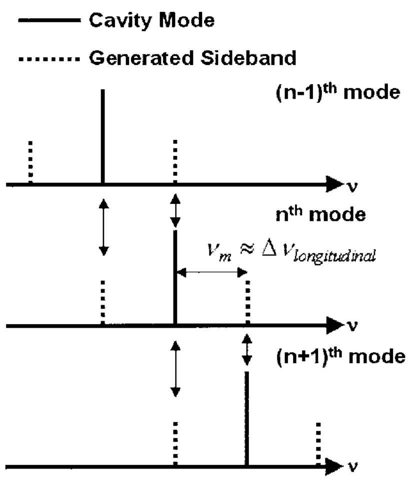
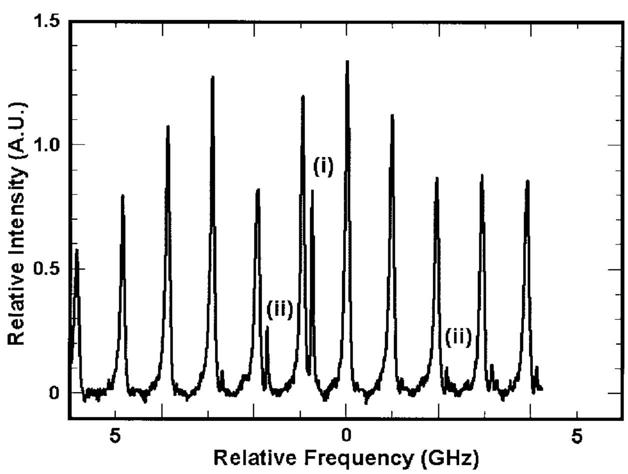


Fig. 8. Pulsewidth at various optical injection levels.



(a)



(b)

Fig. 9. (a) Sideband generation in a mode-locked laser. (b) Generation of sidebands from injected mode: (i) injected signal (i) and (ii) generated sidebands.

locking tones can be seen up to 5 GHz. By monitoring the heterodyne tones at frequencies up to 5 GHz, the generated side-bands from the injected mode would not contribute to the heterodyne tones in Fig. 6(a)–(c) since powers of higher harmonics drop off rapidly with harmonic number. Therefore,

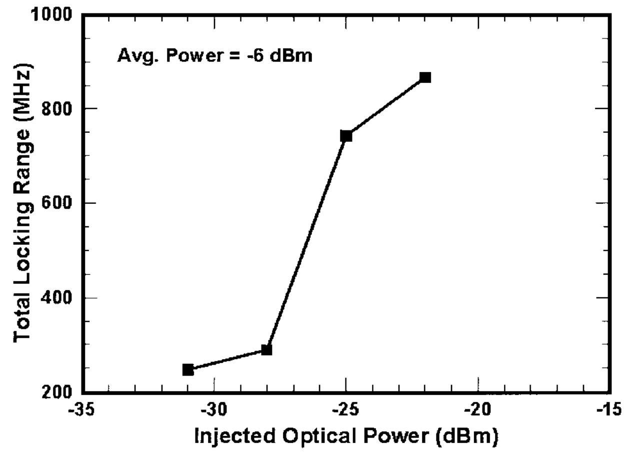


Fig. 10. Locking range at various injected optical powers.

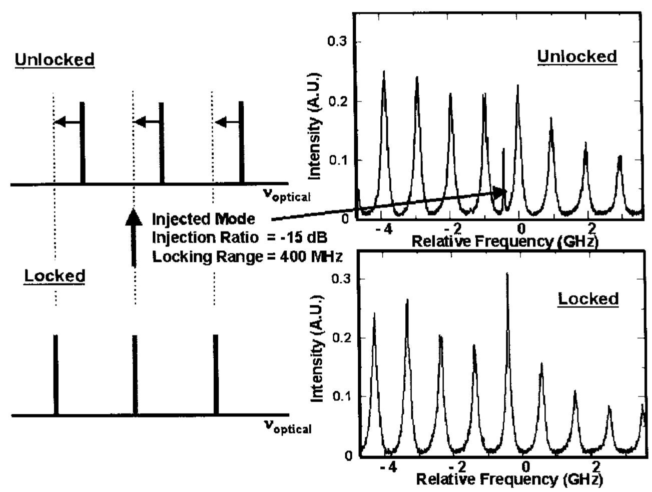


Fig. 11. Pulling of mode-locked laser modes.

the heterodyne tones are due to the beating of the frequency comb with the frequency-shifted master and not from directly generated sidebands. Fig. 10 shows the total locking range at various injection levels and is shown to increase with increasing injected optical power, similar to that of CW injection locking. The average power of the mode-locked laser measured outside the cavity was −6 dBm in this case.

The entire frequency comb does not pull uniformly; modes far away are not affected significantly by the injected light. This is evident in the heterodyne detection RF spectrum. The tones at 19 GHz are much more sensitive to the tuning of the master laser, indicating modes far away are not well locked. The inability to perfectly lock the entire OFC will limit the ability to use all the modes as local oscillators. The imperfect AR coating (≈1%) modulates the gain profile by the monolithic mode spacing, which gives rise to multiple supermodes and a nonuniform channel response. Fig. 11 shows the pulling of the frequency comb. With an injection ratio of −15 dB, the modes can be pulled approximately 400 MHz, which gives a total locking range of 800 MHz. The locking range cannot be larger than the mode spacing (1 GHz) since there will be a mode within 500 MHz of the injected signal. The locking range appears to be symmetric, whereas injection locking of CW lasers results in an asymmetric locking range skewed toward negative frequency detuning [37], [38]. A larger mode spacing, which eliminates the effects of neighboring modes, is required to determine the exact symmetry of the locking range. This can be achieved with monolithic mode-locked semiconductor lasers. Similar to injection locking of CW lasers, the locking range is expected to be a function of the cavity Q and the operating point of the laser. Again, the low average power of the mode-locked laser indicates that the laser is slightly above threshold and is limited by the saturation intensity of the saturable absorber. Also shown in Fig. 11 is an increase in power of the injected mode due to optical injection; at sufficiently high optical injection levels, this single mode will dominate and the slave laser will operate as a single-mode laser.

Since the laser is hybrid mode locked, it is difficult to characterize how much pulse shaping the saturable absorber contributes compared to the modulator section. To achieve mode locking, the reverse bias on the saturable absorber is increased until nearly 100% modulation depth of the pulses is observed in the autocorrelation trace. When this condition was obtained, an RF drive of less than +10 dBm is applied to help stabilize the pulses. Due to the large impedance mismatch between the microwave probe and the laser (measured $Z_{\rm in} = 5 + j25$), less than 25% of the RF power is used to drive the laser. A larger spectral pulling range is expected for passively mode-locked lasers than for actively mode-locked lasers.

V. Potential Applications

As the bandwidth of photodetectors and electrooptic modulators continue to increase beyond 100 GHz, the electronics that process these signals at the receiver end have not kept pace with the rapid growth in bandwidth. An approach to alleviate this problem is to exploit the parallel nature of optics to "slice" up the large instantaneous bandwidth into parallel channels of smaller bandwidth (e.g., 1 GHz) for signal processing in the optical domain. Current state-of-the-art electronics can process signals below 1 GHz with very high dynamic range and low crosstalk; however, it becomes challenging for channelizing broad-band signals at millimeter-wave frequencies [39], [40]. In order to monitor the entire frequency range, the receiver must scan over the entire frequency range, which takes a considerable amount of time and lowers the probability of intercept. The acoustooptic (AO) channelizer was proposed in the late 1970's to alleviate the bandwidth bottleneck [3]–[6]. The advantages of the AO channelizer is the fine channel resolution (on the order of several kilohertz). Channel isolation greater than 50 dB and signal-to-noise ratios (SNR's) greater than 70 dB have also been demonstrated [6]. However, the transducers used to generate the acoustic waves can only operate up to several gigahertz of bandwidth.

An alternative approach to channelize broad-band optical signals is to use a coherent OFC local oscillator in conjunction with a dispersive medium, such as a diffraction grating. A conceptual architecture for this coherent channelizer is show in Fig. 12, where a grating is shown for simplicity. The OFC presented in this paper can potentially be used as the coherent

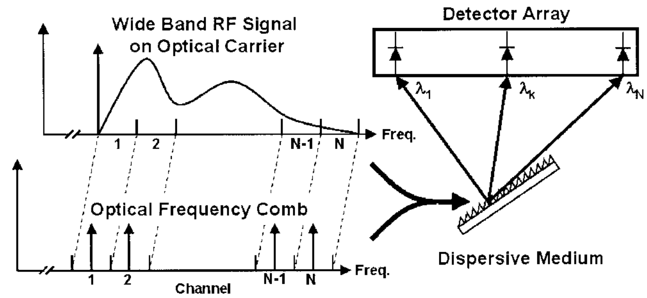


Fig. 12. Channelization of a wide-band RF signal using an injection-locked mode-locked laser.

multifrequency LO's needed for the grating channelizer. Phase coherence between the optical carrier and the OFC is achieved by injecting the unmodulated carrier into the OFC. The desired IF's can be generated on the detector array by offsetting the incident angles of the input signal and the OFC. The use of a dispersive medium is relatively easy and requires no power to achieve spatial separation of the different frequency components. However, to resolve 1-GHz channels using a grating would require a grating width greater than 30 cm and a beam diameter larger than 10 cm, resulting in a rather large optical setup with considerable optical insertion loss. Further engineering is necessary to reduce the size and weight of the channelizer.

VI. Summary

We have demonstrated that CW injection locking of a hybrid mode-locked external-cavity semiconductor laser can provide a local OFC for processing wide-band optical signals. Nearly transform-limited pulses, with pulsewidths less than 2.5 ps, were obtained over a tuning range of 24 nm. This corresponds to a signal bandwidth which can process signals with bandwidths greater than 100 GHz. CW injection locking of a hybrid mode-locked laser is implemented to achieve phase coherence between the incoming optical carrier and the LO. The coherence between the carrier laser and the OFC is dependent on how well the modes of the mode-locked laser are phase locked. Injection locking is also shown to be able to pull the OFC by as much as 400 MHz (corresponding to a total locking bandwidth of 800 MHz), which allows the LO to track small frequency drifts in the carrier signal. Only at injection levels comparable to the average power of the mode-locked laser do the pulses begin to distort and break up. However, perfect locking of modes far away is rather difficult and may limit the spectral width of the coherent OFC.

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