Amplification of high-bandwidth phase-modulated signals at 793 nm

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Received August 16, 2001; revised manuscript received April 16, 2002

Amplification of high-bandwidth phase-modulated optical signals from integrated-optics phase modulators at 793 nm is experimentally demonstrated using an injection-locking technique. Off-the-shelf wide-bandwidth integrated-optics modulators are power limited at 793 nm owing to photorefractive damage of the $LiNbO_3$ waveguides. Typical optical input powers for these devices at this wavelength are less than 10 mW with optical output powers typically less than 1 mW. To amplify the outputs of these modulators, we injected the phase-modulated light into an antireflection-coated 100-mW single-mode diode laser. With the injection-locking technique, small-signal gains of 23 dB are demonstrated with good signal fidelity up to bandwidths of 3 GHz. A bandwidth limitation is found at approximately 3 GHz for sinusoidal phase-modulated signals, above which signal fidelity is seriously degraded. This limitation is significantly less than the measured relaxation oscillations of ~5.6 GHz, suggesting a new limitation to injection locking of phase-modulated signals. Amplification of binary-phase-shift-keyed-modulated signals to 6 Gbit/s is also demonstrated with no bit errors over the 256-bit test sequences.

OCIS codes: 060.5060, 130.3120, 140.3520, 300.6240.

1. INTRODUCTION

Injection locking is a technique used to frequency lock a slave laser to a master laser, or more generally, a technique that transfers the master laser's spectral characteristics to the slave laser. If the master laser has limited optical power, the injection-locking system can be utilized as a small-signal amplifier. The unique physical characteristics of semiconductor diode lasers[1] make them especially attractive for use as injection-locked amplifiers. The short cavity lengths, high gains, and poor cavity finesses in diode lasers result in relaxation oscillations of the order of several gigahertz.[2,3] It has been suggested that the frequency of the relaxation oscillations is the approximate limit for the highest modulation frequency the free-running semiconductor diode laser can support.[4] But the diode laser's unique characteristics also lead to interesting effects for injection locking, including dynamic instabilities and regions of chaos for certain operating conditions.[5–11]

It has been theoretically and experimentally demonstrated that injection locking of semiconductor lasers leads to an enhancement of the direct modulation bandwidth as well as a decrease in the noise characteristics of the slave laser.[4,12–15] These results are promising for the use of diode lasers as injection-locked amplifiers of modulated signals. While diode lasers have been used as injection-locked amplifiers in the past, most of the modulation techniques involved directly modulating the current of the slave laser diode while light was injected from a master laser.[16–20] The largest data rate attained by this approach was 10 Gbit/s (~5-GHz bandwidth).[18] Some other researchers have injected phase-modulated signals into the slave laser, giving good amplification and faithful reproduction for up to 2-GHz sinusoidal phase-modulation frequencies.[21] Pseudorandom frequency or phase-shift keying of the master laser has been demonstrated, showing that data could be amplified at a rate of 1 Gbit/s (~0.5-GHz bandwidth).[22] These two papers reported no degradation in signal fidelity, most likely because the modulation frequencies used were not high enough to reach the frequency of relaxation oscillations of the slave laser. Interest in amplifying frequency-chirped external-cavity diode lasers also led to an investigation of the use of injection locking as a high-power amplifier for ~2-GHz linear frequency chirps.[23] Again good signal fidelity was achieved as well as high gain. These successes gave hope that injection locking of semiconductor lasers could be used as a possible amplification tool for phase-modulated signals in various applications, including high-bandwidth spatial-spectral holographic applications.

High-bandwidth (1–10 GHz) spatial-spectral holography has been proposed as a realistic platform for many optical devices such as low-latency computer memory systems, signal correlators, continuously programmed continuous processors, and broadband true-time delay systems for phased-array radar.[24,25] Currently one of the most promising spatial-spectral holographic materials is Tm^{3+}: YAG because of its relatively low spectral diffusion and high inhomogeneous-to-homogeneous absorption-band ratio.[26] Current off-the-shelf integrated-optics modulators, driven at high frequencies, are power limited at 793 nm (the ${}^3H_6$–${}^3H_4$ transition in Tm^{3+}) owing to photorefractive damage of the $LiNbO_3$ waveguides. Typical optical input powers for these devices at this wavelength are less than 10 mW with optical output powers typically less than a milliwatt. This power level is inadequate to demonstrate the desired high-bandwidth applications of spatial-spectral holography, creating a need for reliable high-bandwidth amplification devices at ~793 nm. There has been work on a Tm-doped fiber amplifier in this wavelength range.[27] That approach requires a high-power single-mode pump laser (~1 W), pulsing of the pump laser owing to population dynamics, and cooling of the fiber to 77 K. In the present paper we experimentally demonstrate amplification of high-bandwidth phase-modulated output from integrated-optics modulators at 793 nm and, unlike other research efforts, reveal an upper bandwidth limitation on amplified sinusoidal phase-modulated signals.[21] We then demonstrate the amplification of binary-phase-shift-keyed (BPSK) signals at data rates up to 6 Gbit/s (~3-GHz bandwidths). This data rate is six times higher than in previous demonstrations of BPSK-modulated signals.[22]

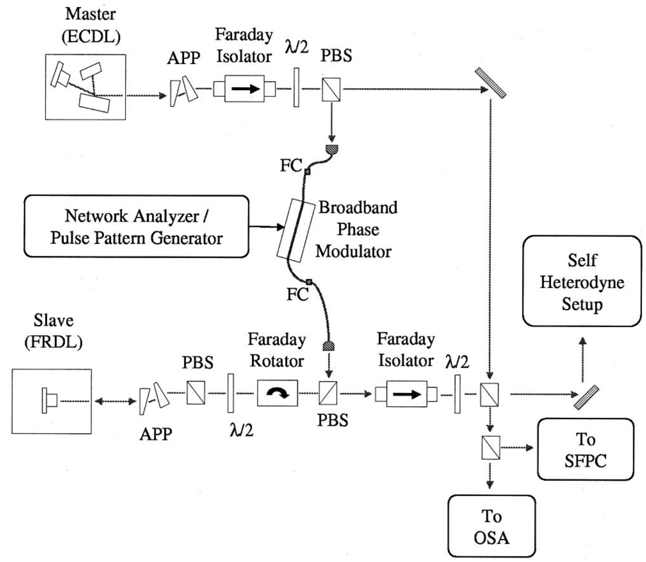

Fig. 1. Optical injection-locking setup with a fiber-coupled integrated-optics phase modulator. See text for discussion.

2. EXPERIMENTAL SETUP

High-bandwidth integrated-optics phase modulators are available commercially as fiber pigtailed units. These units have bandwidths from 1 to over 40 GHz. The modulator used in the following experiments has a 3-dB bandwidth of 13 GHz. Input powers for this device at 793 nm were to be kept lower than 10 mW. The measured insertion loss of 12 dB with the modulator used in these experiments led to output powers for modulated signals of ~800 μW. This modulator was tested with both sinusoidal phase-modulation and BPSK signals. For sinusoidal phase modulation, the modulator was driven by a 13.5-GHz Hewlett Packard 8719ES network analyzer. For BPSK signals the modulator was driven by a 12-GBit/s Advantest D3186 pulse pattern generator and amplifier. This pulse pattern generator is capable of producing binary signals of 0.5–2 V at various multigigabit data rates, which were then amplified to 7 V_{pp} (approximately V_π for this modulator).

The first step toward amplifying the phase-modulated signals was to build a reliable injection-locking system and show that locking could be attained at our wavelength of interest. Figure 1 details the experimental setup for the system. In this experiment, an external-cavity diode laser (ECDL) made in our laboratory and operating in the Littman configuration was used as the master laser. This laser had a measured linewidth of ~100 kHz and could be manually tuned from 780–810 nm. A piezoelectric transducer adjusted the cavity length and allowed for continuous (mode-hop-free) tuning over approximately 65 GHz with a 150-V supply. The output mode of the laser was observed with an optical spectrum analyzer (OSA) and showed typical sidemode suppression ratios of ~40 dB across the tuning range. The slave laser for this experiment, a free-running diode laser (FRDL), was an antireflection (AR)-coated semiconductor diode laser operating at approximately 793 nm. This laser was originally a 100-mW single-mode diode laser; after AR coating it produced 90 mW of output power with a threshold current of approximately 40 mA. Above threshold a single-mode output was observed with a sidemode suppression ratio of 25 dB. An AR-coated slave was chosen for two reasons. First, the relaxation oscillations of such a slave laser were expected to be greater than in noncoated lasers owing to shorter cavity lifetimes.[1] Second, the modes for the cavity become less distinguishable when there is a low-reflectance output coupler, and the laser acts more like an amplifier. This allows, at least in theory, easier injection locking of the slave laser.

In any injection-locking system, the injected field must be coupled into the cavity. To do this and still allow for spatial isolation of the output field can be tricky. In this case, a Faraday rotator and linear polarizers were used to spatially isolate the injected field from the output field. As shown in Fig. 1, the light from the master laser travels first through an anamorphic prism pair (APP) for beam shaping and then through an optical isolator giving greater than 40 dB of isolation. The beam is then passed through a half-wave plate and polarizing beam splitter to allow adjustment of the optical power sent to the slave laser without having to adjust the ECDL directly. The complementary output from the cube is used to monitor the properties of the master laser. The output going to the slave laser is next passed through another half-wave plate (for adjustment of the polarization axis) and then fiber-coupled to a single-mode-polarization-maintaining fiber optimized for 800 nm. The coupling efficiency was ~60%. This fiber could then be attached either directly to a fiber coupler on the slave side of the experiment or to the pigtailed phase modulator for the phase-modulation experiments. The output from the fiber was then passed into the complementary output of a polarizing beam splitter and injected into the slave laser.

The light from the slave laser passed through an APP and, effectively, two Faraday isolators. For alignment, the wave plate before the Faraday rotator could be adjusted to allow the slave laser to pass to a single-mode fiber coupler. The coupling efficiency at this location was typically 60%. This fiber could then be attached (as discussed above) directly to the fiber from the master or to the output of the pigtailed phase modulator. After alignment, the wave plate before the Faraday rotator was adjusted so that the slave laser passed through the polarizer and on to a 40-dB isolator. A half-wave plate and polarizing beam splitter combination was used after the final isolator, allowing a small portion of the output to be analyzed simultaneously with the optical spectrum analyzer and a scanning Fabry–Perot cavity (SFPC). The latter was a Coherent 240 with a 7.5-GHz free-spectral range and a finesse of 150. The main portion of the beam passed through the polarizer to the chosen experiment. This optical configuration allowed maximum injected fields while maintaining isolation of the master laser from the slave laser.

3. MEASUREMENTS AND ANALYSIS

A. Initial Injection-Locking and Locking Regions

The modes of the master laser and the slave laser before and after injection locking were examined with the OSA. Figures 2(a), 2(b), and 2(c) show the master laser's optical spectrum, the slave laser's spectrum before injection locking, and the slave laser's spectrum after injection locking in a stable region, respectively. Upon injection of the master laser, the slave laser jumps to the carrier frequency of the master, and the sidemode suppression ratio of the slave laser increases from 25 to 35 dB. There is still evidence of the original facet modes of the slave laser and these play an important role in the carrier frequencies at which injection locking can take place. In order to injection lock, the free-running frequency of the AR-

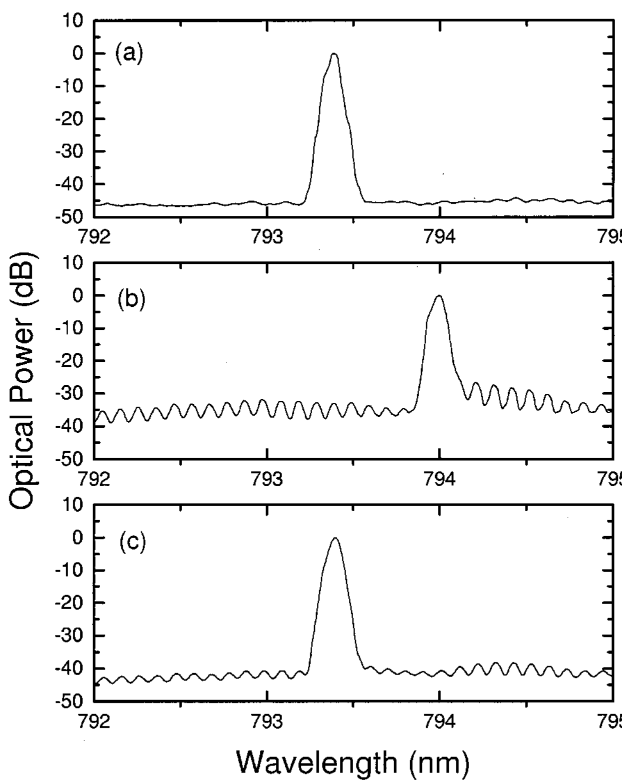

Fig. 2. Optical spectra of (a) master laser, (b) slave laser before injection locking, (c) slave laser after injection locking.

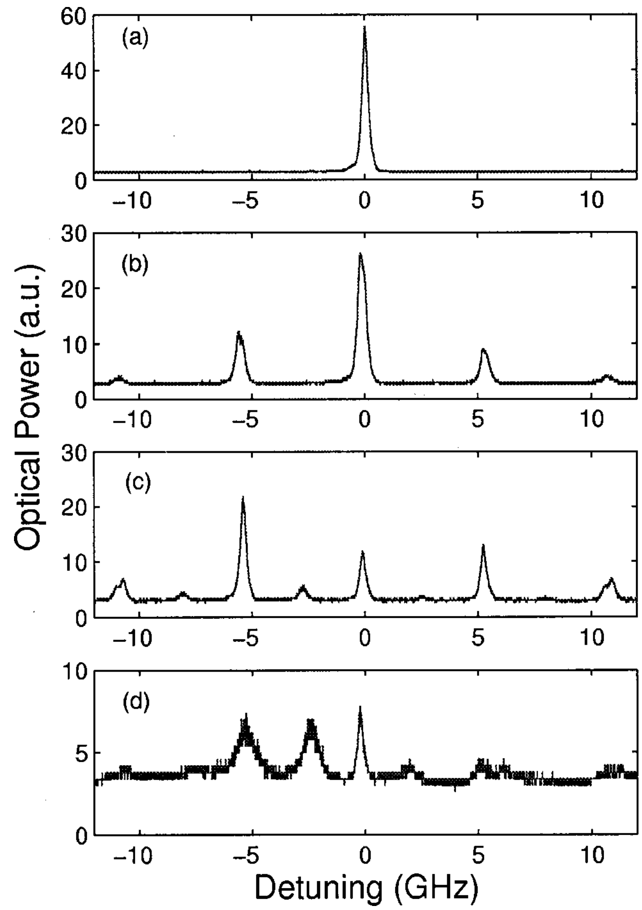

Fig. 3. Optical spectrum of the different regions on the period doubling route to chaos showing (a) stable locking, (b) undamped relaxation oscillations, (c) period-doubled relaxation oscillations, (d) the chaotic region.

coated slave laser did not have to be close to the frequency of the master. As long as the master laser was positioned close to a facet mode of the slave laser, the slave would be injection locked.

The standard period doubling route to chaos was observed by locking the slave laser with low injected powers and then increasing the injected power for zero detuning.[11] To our knowledge this has not been observed before with an AR-coated diode as a slave laser. There are four main regions as the injected power is increased; the characteristic optical spectra for each region are shown in Fig. 3 for a slave output of $P_{\text{out}} = 88$ mW. The four spectra shown represent regions of (a) stable locking shown with $P_{\text{in}} = 9\ \mu$W, (b) undamped relaxation oscillations shown with $P_{\text{in}} = 70\ \mu$W, (c) period-doubled relaxation oscillations shown with $P_{\text{in}} = 132\ \mu$W, and finally (d) the chaotic region shown with $P_{\text{in}} = 352\ \mu$W.

The relaxation oscillations of the free-running slave laser, measured with a heterodyne technique,[3] increased as a function of injected current as expected. At the operational point of $P_{\text{out}} = 88$ mW, the relaxation oscillations were measured to be $\nu_r = 5.6$ GHz, in good agreement with the period-one oscillation sidebands $\nu_{P1} = 5.5$ GHz obtained from Fig. 3(b). Previously it was thought that the maximum modulation frequency for amplification of phase-modulated signals would be close to these 5.5-GHz sidebands.

To identify the region of stable locking where faithful reproduction of modulated signals can be expected, a map of the dynamic instabilities had to be determined as a function of detuning and injection level. Figure 4 is a map of these regions and shows good agreement with features found by using non-AR-coated diodes and distributed feedback lasers.[28,29] This map was produced by increasing the injected power level from $P_{\text{in}} = 0.8\ \mu\text{W}$ to $P_{\text{in}} = 792\ \mu\text{W}$ and stepping the master frequency ν_M from -10 to $+10$ GHz with respect to the nearest facet mode frequency ν_S of the free-running slave laser. The detuning parameter has been defined as $\Delta\nu = \nu_S - \nu_M$. The injection ratio is defined as the input power directly in front of the slave laser cavity divided by the output power of the slave without inclusion of cavity-coupling factors. The defined regions on the map are stable locking (S), undamped relaxation oscillations (P1), period-doubled relaxation oscillations (P2), chaotic regions (C), four-wave mixing (4W), multilongitudinal mixing (M), period-four relaxation oscillations (P4), a combination region of chaos and relaxation oscillations (U), as well as regions that were unlocked. The different markers on the map delineate observations of the approximate boundaries between regions. The lines and shading are interpolated and intended to guide the eye.

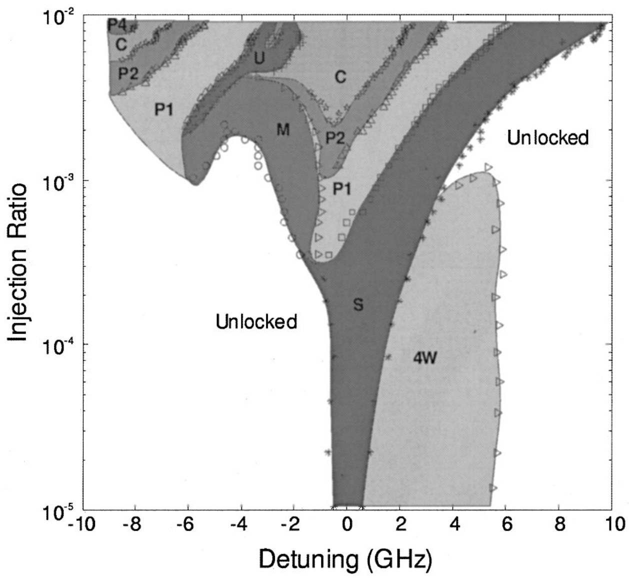

Fig. 4. Observed regions of injection locking versus the detuning and the injection ratio ($P_{\text{in}}/P_{\text{out}}$ as measured just outside the slave). The symbols represent observations of the boundaries between different regions, while the lines and shading are there to guide the eye. The various regions are stable locking (S), undamped relaxation oscillations (P1), period-doubled relaxation oscillations (P2), chaotic regions (C), four-wave mixing (4W), multilongitudinal mixing (M), period-four relaxation oscillations (P4), an undefined region of both chaos and relaxation oscillations (U), as well as unlocked regions.

B. Amplified Sinusoidal Phase Modulation

Once the region of stable locking had been adequately mapped, the slave laser was injection locked in that region with a phase-modulated optical signal. First, the system's response to sinusoidal phase modulation was examined. The phase modulator, operating with sinusoidal phase modulation, was tested without injection locking to ensure that the modulator's output was as expected. This was done by recording optical spectra with the SFPC and a computer-controlled digitizing oscilloscope. The left-hand panels in Figs. 5(a) and 5(b) show the master laser's spectrum when phase modulated at 1 GHz and 3 GHz, respectively. The modulation frequency was then

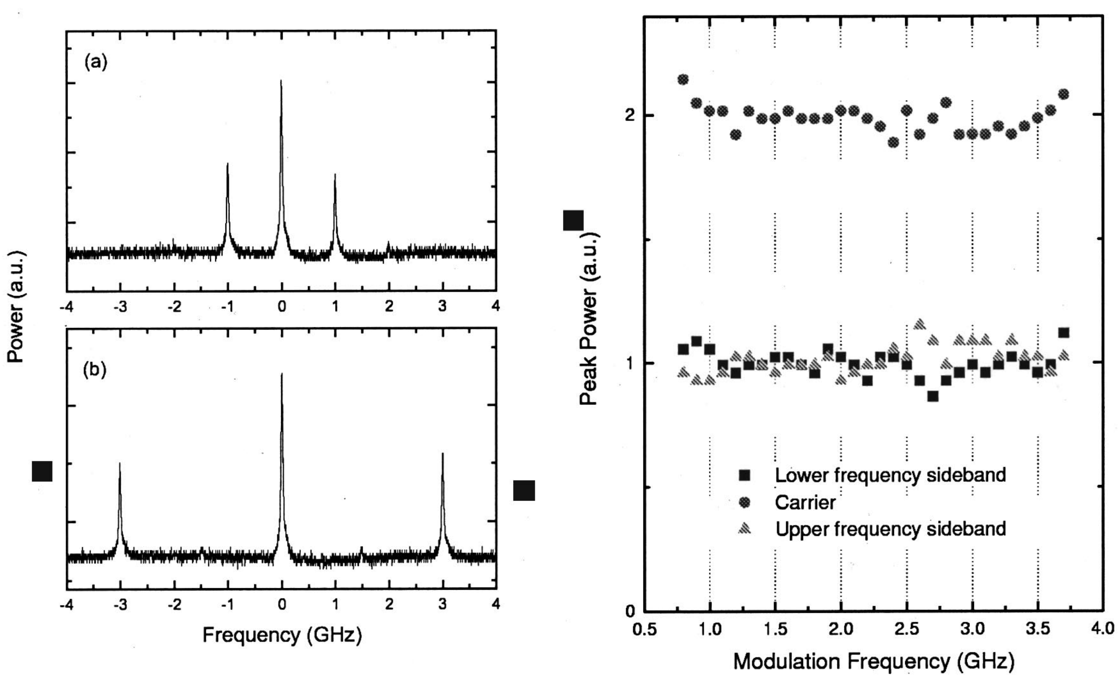

Fig. 5. (Left) Sinusoidal phase modulation of the master laser with modulation frequencies of (a) 1 GHz and (b) 3 GHz. (Right) Plot of the peak powers versus modulation frequency for the carrier and sidebands of the phase-modulated master. At each modulation frequency the rf power was adjusted to achieve roughly a 2:1 ratio of carrier to sideband power.

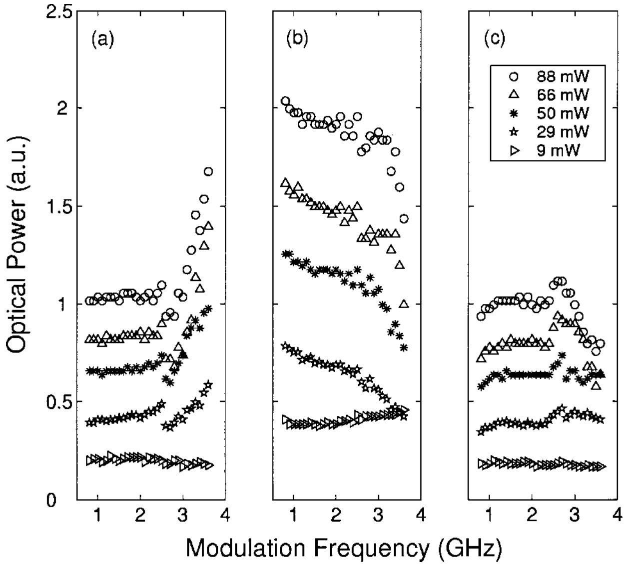

Fig. 6. Injection-locked peak powers versus modulation frequency for (a) lower-frequency first-order sideband, (b) carrier, (c) upper-frequency first-order sideband. The different power levels correspond to gains of 14, 18, 20, 22, and 23 dB.

stepped from 0.8 to 3.4 GHz in steps of 0.1 GHz. At each step, the optical powers of the master laser carrier and the lower- and upper-frequency first-order sidebands were measured. These powers are plotted as a function of the modulation frequency in the right-hand plot of Fig. 5. Due to nonlinearities in the modulator, a set of appropriate input rf powers had to be found for the series of modulation frequencies to give an ~2:1 ratio of carrier power to first-order sideband power. The 2:1 ratio was picked to help determine signal fidelity in the injection-locked signals and to reduce the second-order sidebands.

A set of measurements was made for several different output powers—$P_{\mathrm{out}} = 9, 29, 50, 66$, and 88 mW—of the slave laser giving gains of 14, 18, 20, 22, and 23 dB, respectively. The injected light was $P_{\mathrm{in}} = 400\ \mu\mathrm{W}$ for all slave powers. The detuning was adjusted to center the system in the stable locking region for the given injection ratio. The output of the injection-locked slave laser was recorded with the SFPC for each modulation frequency and for each different value of slave output power. Figure 6 plots the optical powers of the carrier and sidebands as a function of the modulation frequency. Figure 6(a) shows the lower-frequency sideband, 6(b) the carrier, and 6(c) the upper-frequency sideband. Each measurement set for a given value of slave output power was obtained within a 2-min time frame, thereby eliminating long-term laser or SFPC frequency drift. Figure 6 shows that locking was achieved for each level of output power. However, the signal fidelity is degraded as the modulation frequency increases. The ratio of carrier to sideband power deviates by ~20% at 3 GHz for $P_{\mathrm{out}} = 88$ mW. At higher modulation frequencies the fidelity of the signal is rapidly degraded, with the lower-frequency sideband increasing in power while the higher-frequency sideband and carrier are depleted of power. In fact, this trend is noticeable at all output power levels. This asymmetry in the sidebands is a significant problem and leads to unwanted amplitude modulation of the output signal. From the discussions above, one might expect that the maximum modulation frequency would be approximately the relaxation oscillation frequency. This frequency, as stated above, was measured to be $\nu_r = 5.6$ GHz for $P_{\mathrm{out}} = 88$ mW. Here one notices that the maximum modulation frequency without serious asymmetry in the sidebands is roughly 3 GHz for all output powers except for 9 mW. Thus, an upper limit for phase modulation has been reached and does not appear to be dependent on the output power of the slave except at very low output powers (9 mW). Unfortunately this limit is less than the expected value of $\nu_r = 5.6$ GHz. This upper limit is likely the result of a set of complex physical processes within the injection-locked diode laser and will need to be simulated to identify the key physical parameters involved in its determination. Simulations are currently being pursued to study this effect further, but are beyond the scope of this paper.

The residual amplitude modulation at the modulation frequency caused by asymmetric sidebands was also measured with a fast detector and the network analyzer. The residual amplitude modulation was measured directly after the phase modulator to characterize the phase modulator's performance and after injection locking at the output of the system. We found a significant increase in residual amplitude modulation above 3 GHz for the locked signals consistent with the onset of asymmetric sidebands shown in Fig. 6.

C. Broadband Operation with Binary-Phase Shift Keying

To explore the slave laser's ability to reproduce a digital signal faithfully, the pulse pattern generator was used to

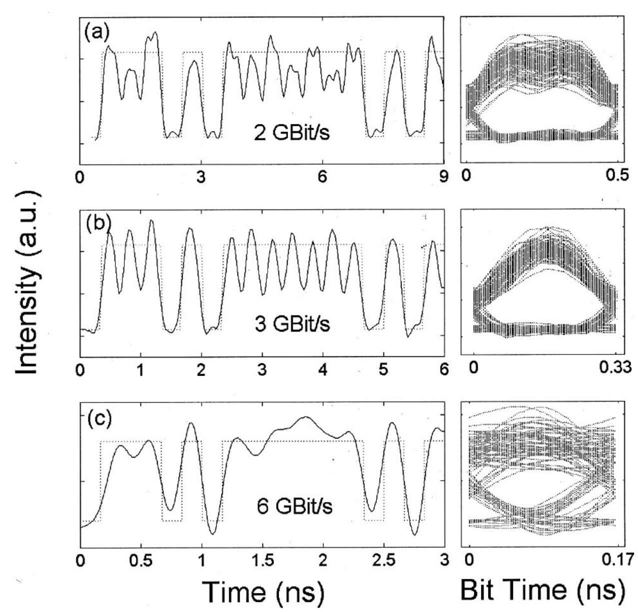

Fig. 7. Bits 1 through 15 of the delayed-self-heterodyne injection-locked outputs of BPSK data at (a) 2 Gbit/s, (b) 3 Gbit/s, (c) 6 Gbit/s. Expected output shown as dotted curves. To the right of each data sequence is the eye diagram for the total 256-bit test sequence.

produce a set of test binary data sequences. Three test data rates were chosen: 2, 3, and 6 Gbit/s. The upper limit on the data rate was set at 6 Gbit/s because of the 3-GHz bandwidth limit of the 10-gigasample/s digitizing oscilloscope used to capture the outputs. The output data sequences were delayed self-heterodyned to allow us to observe the phase shifts. To help adjust the phase of the delayed signal, the beginning of the data sequence was padded with 1's. The piezo-loaded mirror was adjusted so that the padded region would destructively interfere at the output port.

The laser was set to operate within the stable locking region defined above. The BPSK phase-modulated field was then injected into the slave laser. The input power just outside of the slave laser was $P_{\mathrm{in}} = 400\ \mu\mathrm{W}$. The delayed self-heterodyned output from the injection-locked slave is shown in Figs. 7(a) for 2 Gbit/s, 7(b) for 3 Gbit/s, and 7(c) for 6 Gbit/s. The output power for these sequences was $P_{\mathrm{out}} = 88\ \mathrm{mW}$, giving a gain of 23 dB. The expected delayed-self-heterodyned output is shown as a dotted curve in each plot. It can be seen from these plots that the injection locking follows the expected output well for each bit rate. Over the 256-bit test sequences employed, no logic errors were observed. The eye diagrams of the 256 test bits for each data rate are shown next to each of the example signals in Fig. 7. As might be expected, the 6-Gbit/s eye diagram is slightly less open than the other two. This could be the result of a combination of factors including the upper bandwidth limitations of the oscilloscope, as well as the upper bandwidth limitations of the injection locking evidenced by the sinusoidal phase modulation results above. This reproduction of the binary signals up to 6 Gbit/s represents a sixfold increase in the BPSK data rate of injection-locked signals over previous demonstrations.[22]

4. CONCLUSION

In this paper we have demonstrated small-signal amplification by using injection locking of semiconductor diode lasers. The system described here was fully capable of amplification to 6 Gbit/s ($\sim$3-GHz bandwidths) with 23 dB of amplification. Input signals of 400 μW were amplified with an AR-coated single-mode diode laser as the slave. Unlike the experiments performed by Andrekson *et al.*,[21] the modulation frequency for the sinusoidal phase-modulated signals was large enough to encounter a fundamental limit that introduced a significant asymmetry in the phase-modulation sidebands. This suggests that at these injected powers there is a limit to the phase-modulation bandwidth of the diode laser that is less than the frequency of the relaxation oscillations. Future work on this subject should explore the physical mechanisms that limit the phase-modulation bandwidth to less than the relaxation oscillations of the slave laser. This is an important consideration, as it would be desirable to phase modulate beyond 3-GHz bandwidths. Perhaps, as discussed in Refs. 4 and 12–15, with stronger injected fields the modulation bandwidth of the slave laser can be enhanced, allowing these higher bandwidths to be amplified. This reliable amplification technique would be useful in applications such as high-bandwidth spatial-spectral holography that require higher powers.

ACKNOWLEDGMENTS

We thank Pete Roos and Lei Meng from John Carlsten's laboratory at Montana State University for help with the initial discussions and demonstrations. We also thank Vassilios Kovanis for general discussions and suggestions about injection locking. We are grateful to Kelvin Wagner of the University of Colorado—Boulder, to William Miceli of the Office of Naval Research, to Steve Pappert of U.S. Navy Space and Naval Warfare Systems Command, and to the U.S. Office of the Secretary of Defense, Director of Defense Research and Engineering, through the Multidisciplinary University Research Initiative program grant N00014-97-1-1006. Spectrum Laboratory acknowledges support under NASA-Ames Research Center grant NAG2-1323.

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