Digital Transmission with Intracavity Loss Modulated Quantum Well Distributed Feedback Lasers

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Abstract—**We show by experiment and calculation why digitally switched voltage controlled intracavity loss modulated quantum well distributed feedback lasers are well suited for medium haul fiber transmission. A comparison is made between temporal profiles and time resolved optical spectra of regular injection current modulation and intracavity loss modulation. We illustrate our results by demonstrating penalty free digital transmission at a 1.7 Gb/s^{-1} data rate over a 36 km span of single-mode optical fiber.**

DYNAMIC spectral broadening (or chirp) occurs when a laser diode is switched at high speeds. Chirp arises from carrier density variations in the laser active region during switching. In fiber-optic transmission, fiber dispersion causes a wavelength dependent redistribution of optical power in contiguous bit slots which leads to degradation of the decisions capability of the receiver circuitry called dispersion penalty. Thus, laser chirp places restrictions on data rates and transmission spans in optical communication systems which use dispersive single-mode fiber. These restrictions have previously been addressed using sophisticated electrical pulse shaping techniques in individual optimized laser driver circuits [1].

In standard optical fiber, at wavelengths around $\lambda = 1.5$ μm, red light propagates more slowly than blue light. In a current switched laser, the leading edge of an optical pulse has a blue-shifted spectral component and a red-shifted trailing edge. Consequently, such a gain-switched pulse disperses out of the bit slot on both sides as it propagates in a standard fiber. In this letter, we compare the modulation and spectral characteristics of a conventional current modulated multiple quantum well (MQW) distributed feedback (DFB) laser and a voltage controlled, intracavity loss modulated (ICLM) MQW DFB laser. We show that the leading edge of optical pulses from digitally modulated ICLM lasers also have an associated blue-shift but that the trailing edge, however, has virtually no spectral shift. Pulses with these spectral characteristics will degrade system performance only when the span length is such that the leading edge has propagated through the dead time due to the laser turn-on delay. Only beyond that span will a dispersion penalty appear. We confirm these results by demonstrating penalty-free digital transmission over a 36 km span of single-mode optical fiber at a 1.7 Gb/s^{-1} data rate.

The laser structures used for these experiments were InGaAs/InP buried heterostructure multiple quantum well graded-index separate confinement heterostructure (BH-MQW-GRINSCH) DFB lasers grown by atmospheric pressure metal-organic vapor phase epitaxy (MOVPE) on a first order grating prepared on a < 100 > -oriented n-type InP substrate (see [2] for growth details). After crystal growth, BH lasers were formed by mesa stripe etching, reducing the width of the active region using a selective etch and finally regrowing semi-insulating Fe-InP, again using MOVPE. Using standard etching and metalization techniques, front-side electrical contact to the n^+ and p^+ layers is achieved. The wafer is then cleaved yielding DFB lasers with a voltage controlled saturable absorption section [3] as shown schematically in Fig. 1. The electrical isolation between the large gain section and the small intracavity absorber section was > 3 kΩ.

Fig. 2(a) shows the measured laser spectrum (plotted on a logarithmic scale) when a 1.7 Gb/s^{-1}, $2^{15} - 1$ pseudorandom bit stream (PRBS) is applied to the small 50 Ω terminated intracavity absorber. For comparison, the dc laser spectrum is also shown. The spectrum of the ICLM laser exhibits pronounced asymmetric broadening [4], showing a large chirp to the blue side of the lasing mode. Within instrumental resolution, the laser spectrum does not exhibit chirp on the red side of the laser line. The corresponding spectra for a regular current controlled DFB laser is shown in Fig. 2(b). Both red- and blue-shifted components are clearly visible. The physical origin of the pronounced asymmetry for ICLM may be understood by referring the Fig. 3 where we show the laser output calculated by a large signal analysis using single-mode rate equations, experimentally determined data and standard laser parameters [3], [5] for a ..01010.. -1.0 V $\le V_s \le 0.8$ V bit stream at 1.7 Gb/s^{-1} applied to the absorber section. The calculated optical output [Fig. 3 (top)] exhibits a giant, critically damped, overshoot which rapidly stabilizes to a constant (on) level. The calculated behavior of the carrier density [Fig. 3 (bottom)] shows that reduction of losses due to saturation of the intracavity absorption leads to a large and rapid decrease in the carrier density of the laser active region. This reduction in carrier density during the emission of the relaxation oscillation spike results

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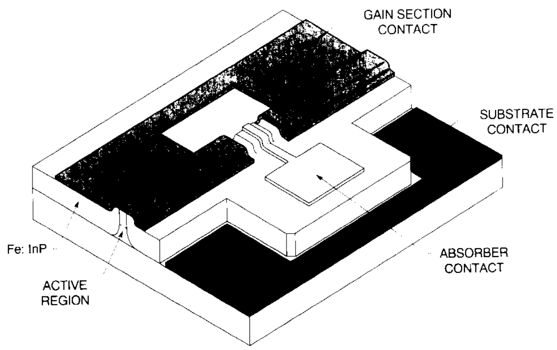

Fig. 1. Schematic of a voltage controlled ICLM MQW DFB laser. The large gain section is pumped with a constant (dc) current I_G, while the laser output is controlled by voltage, V_S, applied to a 50 Ω resistor across the high impedance, small absorber section.

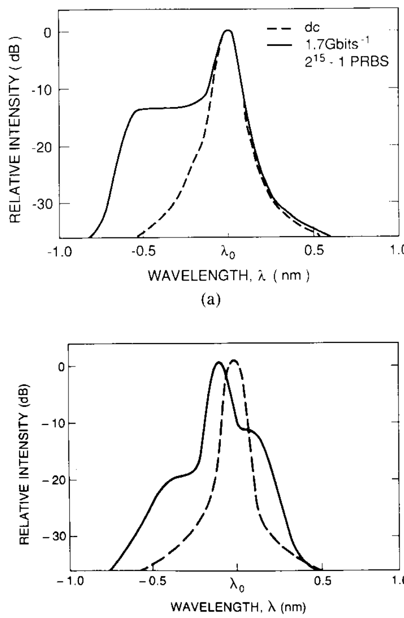

Fig. 2. (a) Experimental time averaged optical spectra for an ICLM laser with a 1.7 GB/s^{-1}, $2^{15} - 1$ 50% mark ratio PRBS applied to the absorber section for I_G = 41 mA and -1.15 V ≤ V_S ≤ 0.85 V. Also indicated is the dc spectrum, offset by 3 dB to clearly illustrate the absence of red chirp using this modulation scheme. (b) Experimental time averaged spectra for a MQW DFB laser conventionally modulated with a current, I_M 10.0 mA ≤ I_M ≤ 50.0 mA (I_{th} = 14 mA). together with its dc spectrum. The spectrometer resolution is 1.0 Å and λ_0 = 1.524 μm for the ICLM laser and 1.560 μm for the conventionally modulated DFB laser.

in the overshoot being spectrally blue-shifted with respect to light emitted during the steady (on) state. When the laser switches off, the carrier density increases leading to a blue-shifted trailing edge. Due to the rapid switch-off, however, very little energy is contained in this portion of the pulse. The width of the laser spectrum remains small due to the rapidity with which the optical output makes transitions between the on and off states. The brevity of the transitions and extent of carrier number excursion combine to make the peak to (blue) pedestal ratio large [5].

Fig. 4 (a) and (b) show experimentally how dispersion in standard single-mode fiber acts upon this blue chirped output of ICLM lasers. Fig 4(a) is a streak camera recording of a bit prior to launching into an optical fiber. Fig. 4(b) shows the bit after traversing 36 km of single-mode fiber. The blue spectral component of the giant spike has dispersed and moved into the turn-on delay region. Distortion of the trailing edge is not apparent, a consequence of negligible trailing edge chirp. Fig. 4 (c) and (d) show corresponding streak camera recordings for a current modulated DFB laser. In this case, the initial spike of the optical pulse is less pronounced than for ICLM leading to less blue-shift at the leading edge. After propagation through 36 km of fiber, a broad pedestal has emerged from both sides of the bit. The evolution of this pedestal continuously degrades signal to noise with increasing

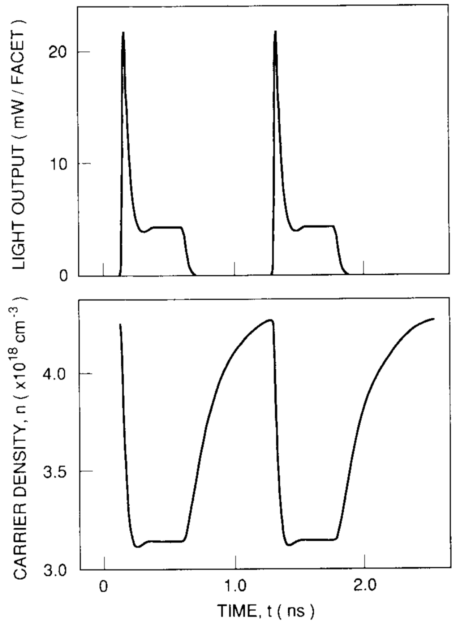

Fig. 3. Calculated (top) optical output and (bottom) carrier density variation for a voltage controlled ICLM MQW DFB laser switched by a ..01010.. 1.7 Gb/s^{-1} data stream.

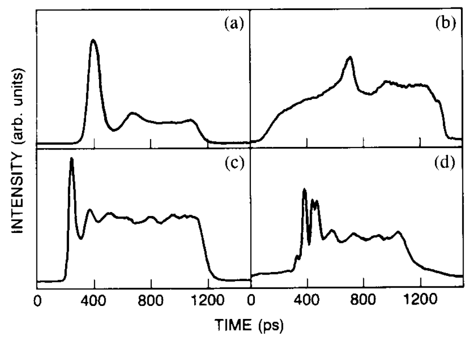

Fig. 4. Streak camera recordings of (a) a bit from an ICLM laser prior to launching into an optical fiber. I_G = 37 mA and -1.3 V ≤ V_S ≤ 0.35 V. (b) The bit after traversing 36 km of single-mode fiber. (c) A bit from a conventionally modulated laser at 0 km and (d) after traversing 36 km of single-mode fiber. 10.0 mA ≤ I_M ≤ 50.0 mA. The duration of the electrical pulse applied to the lasers was 1.0 ns.

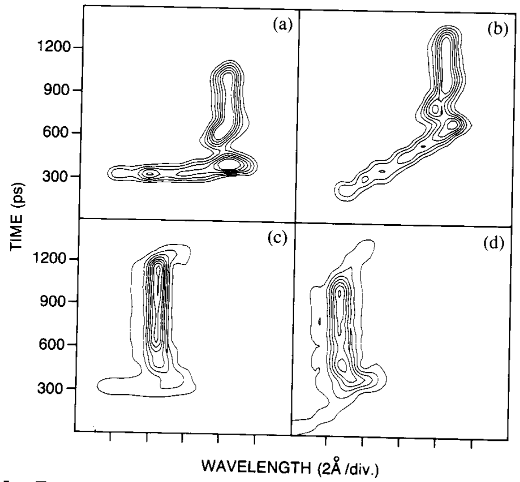

Fig. 5. Topographical plots of time resolved spectra for both modulation schemes under identical conditions to Fig. 5. (a) ICLM at 0 km. (b) ICLM after propagating 36 km in optical fiber. (c) Conventional modulation at 0 km and (d) after propagating 36 km in optical fiber.

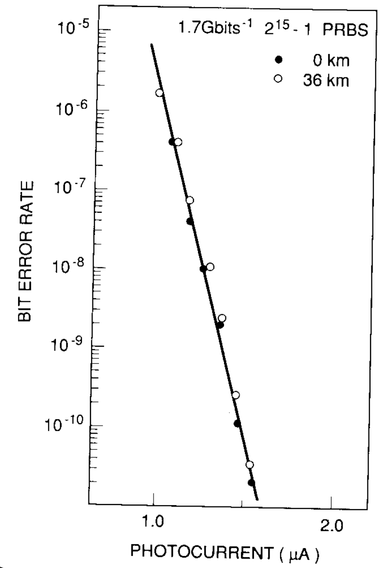

Fig. 6. BER versus received optical power plotted for transmission over 0 and 36 km span of standard single-mode fiber using a voltage controlled ICLM MQW DFB laser for the same conditions as Fig. 2 (a). The absence of a dispersion penalty is to be noted.

transmission length. If this pedestal is ignored, the full width at half maximum of the remaining pulse decreases slightly due to compressive effects of chirp on the first few relaxation oscillations.

Time-resolved optical spectra at 0 and 36 km were measured in order to more carefully study chirp in these modulation schemes. Temporal traces were recorded at different wavelengths incremented by ~ 0.5 Å using a tunable fiber Fabry–Perot interferometer. Fig. 5 shows a topographical representation of these measurements illustrating spectral evolution of the pulses. The characteristics of the ICLM laser at 0 and 36 km are shown in Fig. 5 (a) and (b), respectively. The leading edge has a pronounced blue-shift which disperses on propagation through the fiber while the trailing edge contains no measurable shift resulting in the absence of a temporal spread at the fiber output. For the case of a current modulated laser shown in Fig. 5 (c) and (d), the leading edge is again blue-shifted. The trailing edge, however, shows a pronounced red shift. This results in pulse spreading at both edges when propagating through the fiber in agreement with Fig. 4. Fig. 5 suggests that dispersion penalty for current modulation increases after a shorter propagation distance than for ICLM. However, at a well-defined fiber span, where the blue-shifted leading edge has dispersed into the next bit slot, the penalty for the ICLM case should increase rapidly. This prediction of dispersion penalty free digital transmission over moderate spans is confirmed by the experimental result of Fig. 6, where bit error rate (BER) versus received optical power is plotted for transmission over a 0 and 36 km span of standard (dispersion $\cong 15$ ps km^{-1} nm^{-1}) single-mode fiber using a voltage controlled ICLM DFB laser emitting at $\lambda = 1.524$ μm. *A dispersion penalty is not observed.*

In conclusion, we have investigated dynamic spectral broadening in transmission systems using digitally modulated MQW DFB lasers. We show that ICLM lasers (despite the very strong blue-shift at the onset of the pulse but due to the absence of significant chirp at the trailing edge) allow dispersion penalty free, high bit rate, digital optical communications over moderate fiber links. We note that this behavior directly results from the carrier dynamics of ICLM lasers and does not require use of sophisticated driver circuitry.

Acknowledgment

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