

External Optical Modulator Using a Low-cost Fabry-Perot Laser Diode for Optical Access Networks

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We propose and demonstrate an external optical modulation method based on TE/TM-mode absorption nulls in a Multiple Quantum Well (MQW) Fabry-Perot laser diode (FP-LD). The center wavelength of the absorption nulls is rapidly shifted to short-wavelength by the small current change (~ 1 mA) in the FP-LD, which can modulate an optical signal with more than 10 dB of extinction ratio (ER). The shift of the center wavelength comes from the refractive index change due to anomalous dispersion and the plasma effect in MQW FP-LD waveguide. Non-inverting and inverting signals are made by TE- and TM-mode absorption nulls at 155.52 Mbps and BERs for the signals are measured.

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I. INTRODUCTION

Recently, Wavelength Division Multiplexing (WDM)-Passive Optical Network (PON) for optical access networks has received a great deal of an attention. WDM-PON has a high security, a protocol transparency, and wide bandwidth compared with Time Division Multiplexing (TDM)-PON. However, WDM-PON typically requires high-cost DFB (Distributed Feedback)-LDs, which becomes a big bottleneck for a commercial deployment. Therefore, many researchers have been intensively trying to find out cost-effective methods for WDM-PON [1-3]. One of the methods is a spectrum-sliced WDM source by optically filtering of an incoherent broadband Amplified Spontaneous Emission (ASE) light such as a LED (Light-emitting Diode) or an EDFA (Er-doped Fiber Amplifier) [1]. The others are based on injection-locked Fabry-Perot laser diode (FP-LD) sources by external coherent [2] or incoherent [3] light. However, the injection-locked FP-LD source may have a demerit of potentially unstable operation due to unexpected behaviors inside the laser diode [4]. On the other hand, the LED light source may be a good candidate for WDM-PON, but its output power is not enough for the purpose. In the case of the EDFA, the spectrum-sliced source has relatively much higher output

power than the LED, but expensive external optical modulators [1] or SOAs (Semiconductor Optical Amplifiers) [5] for signal modulation are needed.

In this paper, we propose and demonstrate an external optical modulator employing a low-cost FP (Fabry-Perot)-LD, which can be effectively used for WDM-PON as an optical access network application. The modulation is based on the shift of TE/TM-mode absorption nulls (by refractive index change) due to anomalous dispersion and plasma effect in a FP-LD. The optical modulated signal with high extinction ratio (> 10 dB) at 155.52 Mbps can be achieved. Based on the proposed optical modulator, a cost-effective WDM-PON architecture is proposed.

II. PRINCIPLE

When a multiple-quantum-well (MQW) type FP-LD is driven over a threshold current, the FP-LD makes light by lasing on TE-mode. On the other hand, TM-mode in the FP-LD shows only absorption nulls not lasing owing to very small TM-gain inside the Fabry-Perot mirror (resonator). If no current is applied to the FP-LD, both modes (TE- and TM-mode) have absorption nulls. As the current increases from 0 mA

to the threshold current, all the absorption nulls are moved to short-wavelength without any lasing on both modes. Even though light due to spontaneous emission occurs, the light at small current level can be ignored in comparison to externally incident light for optical modulation. The wavelength of the incident light is spectrally aligned with the center wavelength of one among the absorption nulls. Thus, optical modulation can be achieved by vibrating the center wavelength of the null due to current signal injection into a PF-LD.

The shift of the absorption null comes from the change of the refractive index in an MQW FP-LD waveguide, which is due to anomalous dispersion, plasma effect, and bandgap shrinkage [6]. However, the bandgap shrinkage can be neglected when an input light wavelength is longer than a bandgap wavelength of the waveguide in the MQW FP-LD [7]. In this case, the anomalous dispersion and the plasma effect become dominant for the refractive index change. The refractive index change due to the plasma effect in a bulky waveguide can be written as follow [6,8].

$$\Delta n = \frac{e^2 N}{2\omega^2 \epsilon_0 \epsilon_r m_c^* n} \quad (1)$$

where, N is a carrier density, n is the refractive index in the absence of the plasma effect, $\epsilon_0 \epsilon_r$ is the dielectric constant of the active region, and m_c^* is the effective mass of the carrier. The total refractive index change due to the plasma effect in a MQW waveguide can be easily obtained by summing refractive index changes in wells and barriers [6]. In (1), because $\omega = 2\pi/\lambda$, the $\sqrt{\Delta n}$ is proportional to an input light wavelength λ . On the contrary, a refractive index change due to the anomalous dispersion according to the wavelength λ is reduced. Therefore, as the input light wavelength increases, the plasma effect is more dominant than the anomalous dispersion. As a result, the total refractive index change becomes almost constant for a wide range of wavelengths (> 100 nm) [6].

Let us consider a modulation speed for the proposed PF-LD modulator. To operate a PF-LD as an optical modulator, the injection current J with less than a threshold current J_{th} must be applied, i.e. carrier density $N < \text{threshold density } N_{th}$. As a consequence, a photon density N_{ph} becomes almost zero, which means a stimulated emission can be neglected. Thus, the rate equation for the carrier density N can be expressed as [9]

$$\frac{dN}{dt} = \frac{J}{qd} - \frac{N}{\tau_e(N)} \quad (2)$$

where, q and d are the charge constant and the thickness of the active layer, respectively. And, $1/\tau_e(N)$

is the effective recombination rate, which $1/\tau_e(N) = A + BN + CN^2$, where AN is the nonradiative recombination rate, BN^2 is the radiative spontaneous rate, and CN^3 is the Auger recombination rate. Because of the carrier dependence term $\tau_e(N)$, Eq. (2) is nonlinear and can be solved numerically or approximately. Assuming τ_e is constant, i.e. $B=C$, we can know easily that the carrier density $N(t)$ increases logarithmically and decays exponentially with the time constant τ_e . Thus, the speed for the proposed modulator strongly depends on τ_e . By the calculation from typical parameter values ($A=5 \times 10^8$, $B=1 \times 10^{-10}$, $C=3 \times 10^{-20}$, $N_0=1 \times 10^{18}$, and $N_{th}=2.61 \times 10^{18}$) in [9], $\tau_e(N_0) \approx 1.58$ nsec and $\tau_e(N_{th}) \approx 1.04$ nsec, which mean roughly 630 Mbps \sim 1 Gbps modulation speed.

III. EXPERIMENTAL RESULTS

Fig. 1 shows the experimental result for absorption nulls with respect to the injection current in a FP-LD, which the laser diode used in the experiment is InGaAsP MQW type. The absorption nulls are made by being kept and dissipated in a FP-LD cavity for the input light with wavelength such that the phase after each round trip has to be an integral multiple of 2π . In other words, $\lambda_p = 2nL/p$, where λ_p is the wavelength of the p th cavity mode, L is the cavity length. When a current is injected, all the absorption nulls are continuously shifted to short-wavelength by negative refractive index change. But, for over the threshold current ($I_{TH} = \sim 11$ mA), the nulls start to move in the opposite direction (to long-wavelength) due to the thermal effect by lasing [10]. Here, it is worth noting that the nulls are rapidly shifted to short-wavelength by a small amount of current from 0 to 1 mA as shown in Fig. 2. The center wavelength of the nulls is

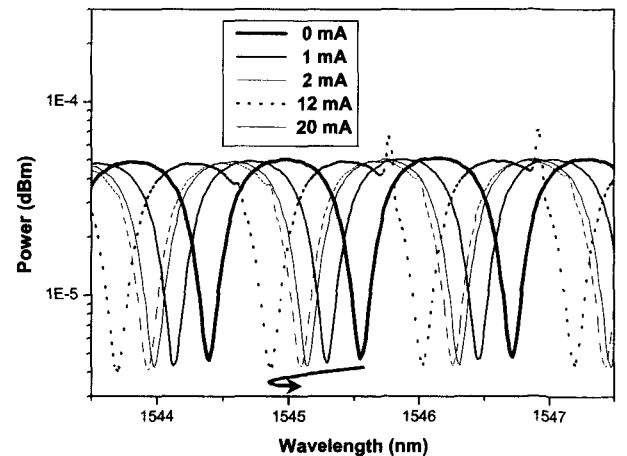


FIG. 1. TM-mode absorption spectra of Fabry-Perot laser-diode (FP-LD) with the current change from 0 to 20 mA.

simultaneously moved by ~ 0.25 nm (~ 30 GHz) due to only 1 mA current, which is enough to modulate the optical signal. The absorption null has the notch filter characteristic of ~ 0.1 nm bandwidth at -3 dB and ~ 19 dB attenuation at the center wavelength. For a small current level such as 1 mA, the spontaneous emission noise generated by the FP-LD itself is negligible compared to the input light.

Fig. 3 shows the experimental setup for an external optical modulation using a low-cost FP-LD. Laser light from the tunable-LD is incident into the FP-LD through PC1 (Polarization Controller), OC (Optical Circulator), PBS (Polarization Beam Splitter) and PC2. By the PC2, the polarization (TE or TM) of the incident light into the FP-LD can be determined. The reflected light from the FP-LD comes out of 3 port of the OC through the PBS. The output signal may have an inverted or a non-inverted data format, which depends on which side (short-wavelength side \rightarrow inverting, long-wavelength side \rightarrow non-inverting) of absorption nulls is used. BERs (Bit Error Rate) for the inverted and the non-inverted signal on TE- and TM-mode absorption null at 155.52 Mbps (2^{31} -1 PRBS) are measured and shown in Fig. 4. Non-inverted signal that is made on the long-wavelength side of the TM-mode absorption null shows the best

BER performance. The worst case, i.e. inverted data signal on the short-wavelength side of the TE-mode absorption null, has ~ 2.3 dB power penalty ($@10^{-9}$). The minimum and the maximum insertion loss of the proposed modulator are 13.5 dB and 10.2 dB for the non-inverted signal on the TM-mode null and for the inverted signal on the TE-mode null, respectively. ERs for all the data show more than 10 dB. The reason why optical modulation by TE-mode shows lower BER performance is that the small lasing beam (even though small current is driven to a FP-LD) inside a FP-LD produces some interferences with external incident light.

The MQW FP-LD used in the experiment has a cavity length of ~ 300 μ m and then shows that the wavelength difference between nulls as shown in Fig. 1 is around 1.17 nm. For the WDM signal with the

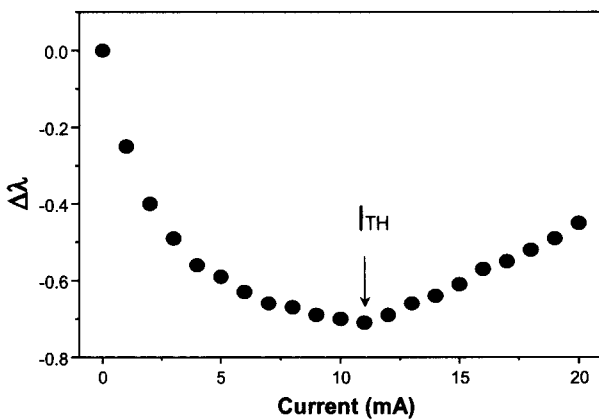


FIG. 2. Center wavelength displacement of the absorption null versus injection current change.

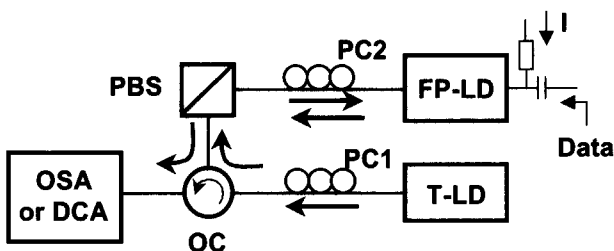


FIG. 3. The experimental setup for the proposed external optical modulator based on the absorption null modulation of a FP-LD.

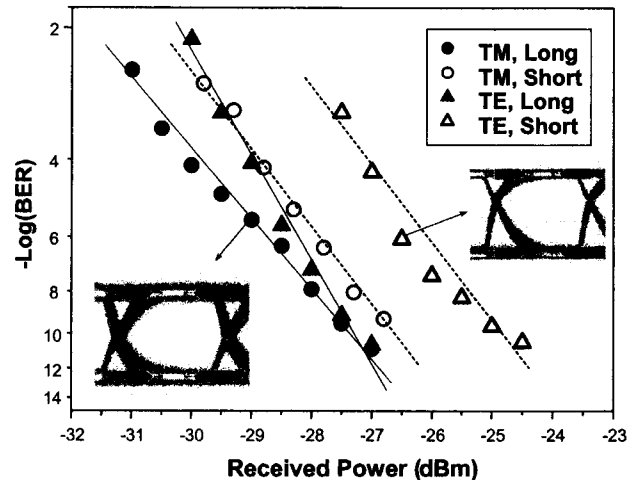


FIG. 4. Measured BER curves and the corresponding eye diagrams for (●) non-inverted, (○) inverted data signal by a TM-mode null and (▲) non-inverted, (△) inverted data signal by a TE-mode null.

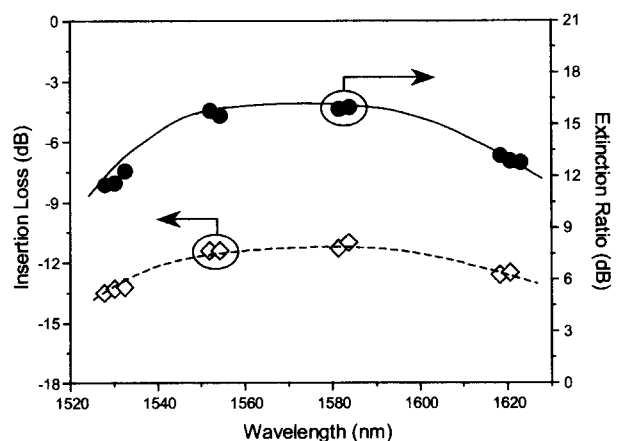


FIG. 5. Measured Extinction Ratio (dB) and Insertion Loss (dB) corresponding to Wavelength.

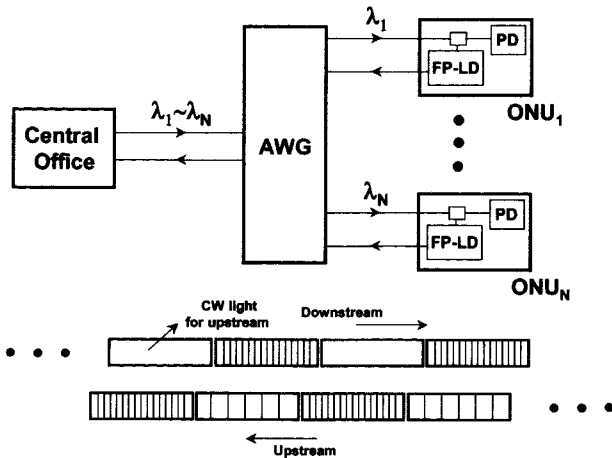


FIG. 6. WDM-PON architecture with the proposed FP-LD modulator.

ITU-T grid, the FP-LD has to be designed to get the optimal cavity length. In order to know the wavelength sensitivity for the proposed FP-LD modulator, we measured ERs (Extinction Ratio) and insertion losses from 1520 nm to 1630 nm at 155.52 Mbps for non-inverting signal on TM-mode nulls as shown in Fig. 5. The proposed FP-LD modulator shows good performances (ERs > 11.5 dB and insertion losses < -13.4 dB) for very wide wavelength range (~100 nm). This result is in very good agreement with the result in [6].

IV. ARCHITECTURE OF WDM-PON

Fig. 6 shows one example of WDM-PON based on the proposed method. Instead of a DFB-LD source (employed in typical WDM-PON) inside the optical network unit (ONU), the proposed FP-LD modulator is used. WDM downstream signals with wavelength $\lambda_1 \sim \lambda_N$ from the central office are wavelength-routed and transmitted to ONUs. As shown in Fig. 6, each signal from the central office is composed of the modulated downstream data for half and the CW light for the other half. Here, the CW (Continuous Wave) light is used for the generation of upstream signal by the FP-LD modulator at the ONU and then routed back to the central office. Similar architectures had been proposed [2,11]. But, in [2], very high-speed downstream signal is required to make the single mode operation of a FP-LD by injection-locking, which may be potentially unstable. Also, in [11], high-cost optical modulators are needed. In contrast, the proposed modulator is based on the absorption nulls in a PF-LD and thus shows very stable operation in a cost-effective way.

V. CONCLUSIONS

In this paper, a new optical modulation method using a low-cost FP-LD was proposed and experimentally demonstrated. Due to the cost-effectiveness, the proposed optical modulator has many applications in optical access networks, optical signal processing, and so on. Even though the modulation speed in the experiment is 155.52 Mbps with more than 10 dB insertion loss, ~1 Gbps modulation and low (~6 dB) insertion loss will be possible with the small modification of a FP-LD such as a length and a reflectance control for the FP cavity.

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