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Study of Several Schemes for Internal Wavelength Locker Integrated 10 Gbps Electro-absorption Modulated Laser Modules in Metro Dense WDM Applications

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Several internal wavelength locker schemes for 10 Gbps electro-absorption modulated laser (EML) module were reviewed. 10 Gbps EML modules with simple and robust internal wavelength lockers for metro dense WDM application were successfully demonstrated. The wavelength aging over 2000 hours was done at elevated temperature of 70℃. The average wavelength drift of 10 modules was measured to be about ± 5 pm. These modules can be successfully applied to the 10 Gbps DWDM systems with 50 GHz channel spacing.

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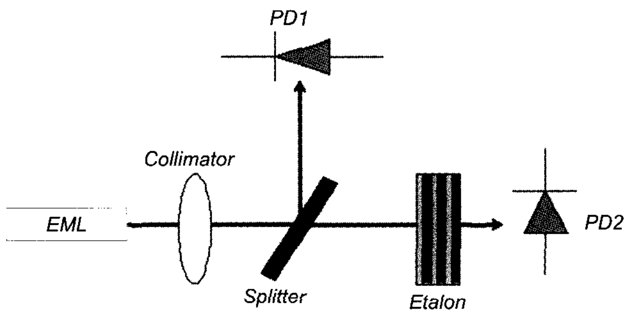
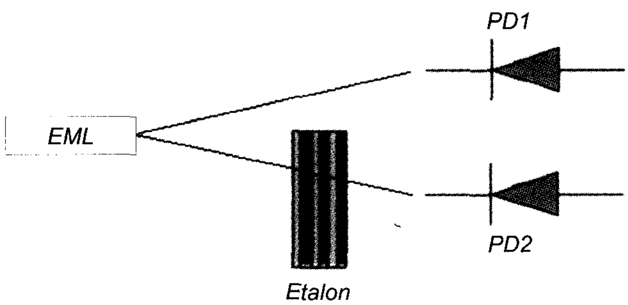
I. INTRODUCTION

In wavelength-division-multiplexing (WDM) systems, the channel spacing of the signals has been defined by ITU-T with the channel spacing $\triangle f$ of 50 GHz (or 0.4 nm) based on a wavelength of 1552.52 nm. It is strongly required for the frequency of each laser to be stabilized within 10% of the channel spacing in order to maintain constant channel spacing and avoid inter-channel crosstalk, that is, the maximum frequency drift should be less than ± 2.5 GHz for $\triangle f$ of 50 GHz [1,2]. However, in general, the wavelength stability over the temperature and over the lifetime of a general single-mode laser diode is not good enough to meet the requirement by itself without proper treatment. Therefore, most of the current WDM sources should be integrated with either external or internal wavelength lockers.

A wavelength locker often consists of a wavelength discriminator such as a Fabry-Perot (FP) etalon and two monitoring photo-diodes (i.e., PD1 and PD2) [3]. A collimating lens and a beam splitter can be added if necessary. Fig. 1 (a) and (b) show schematic drawings of internal wavelength lockers using partially collimated or divergent beams, which are applied in our experiments. PD1 is used to measure the total output power. The monitor current at PD1, I_{PD1} is used as an input for the automatic power control (APC) circuit. A FP etalon filter is mounted in front of the PD2. The monitor current at PD2, I_{PD2} which changes according to the transmittance of a filter, is an indicator of the wavelength itself, and therefore I_{PD2} is used as an input value for the wavelength locking circuit which maintains



(a)



(b)

FIG. 1. Schematic diagram of our internal wavelength locker. (a) internal wavelength locker using partially collimated beam, (b) internal wavelength locker using divergent beam

a desired wavelength with the temperature control of an EML.

The transmittance curve of the FP filter is a periodic Lorentzian for an ideal plane wave input. Thus, the inflection wavelength of each resonance in the transmission spectrum can be used as a locking wavelength. In general, the output beam from the rear facet of the EML chip is not a plane wave and its divergence angle is approximately $35^\circ \times 35^\circ$ in our case. Therefore, if a plane wave as an input beam for a wavelength locker is desired, a light collimation system should be included in an internal wavelength locker.

In this letter, we reviewed intensively several internal wavelength locker schemes for 10 Gbps EML module. We also designed and fabricated 10 Gbps EML modules with simple and robust internal wavelength lockers, which can be applicable to the metro dense WDM system with 50 GHz channel spacing.

II. DESIGN SCHEMES

In our wavelength locker, a single cavity FP etalon filter was used in all schemes. The structure of the etalon filter is

$$glass\,/\,\overbrace{HLHL...LH}^{\text{17 layers}}\,8L\,\overbrace{HLHL...HL}^{\text{18 layers}}\,/\,air\,,$$

where H and L represent $\lambda/4$-thick thin layers with high refractive index n_H=2.055 and low refractive index n_L=1.461, respectively. A 2λ-thick film of $n_{sp}=n_L$=1.461 is inserted between the two reflective film structures. The substrate is a glass with n_{sub}=1.5483 Calculated optical bandwidth from this filter is 0.6 nm and peak transmittance is above 90% for the case of a nearly plane wave input beam.

Fig. 2 shows the calculated transmittance spectra of the FP etalon filter for a different FFP. For the nearly plane wave input as shown in Fig. 2 (a), the peak wavelength λ_p and the inflection point λ_L shift toward shorter wavelength as the incident angle θ increases. The spectrum shape is almost symmetric and the maximum transmittance level T_{max} and the bandwidth $\Delta\lambda$ are nearly same for $\theta \leq 2^\circ$. This resonance curve is repeated periodically for a particular period, namely the free spectral range (FSR) of an etalon, which is determined by the optical thickness of the spacer layer. The spectrum becomes asymmetric and $\Delta\lambda$ increases for $\theta \geq 3^\circ$. Thus, it is essential to use an almost plane and normal incident wave on an etalon for the application of multi-channel wavelength lockers.

Fig. 2 (b) and (c) show the transmission spectra when FWHM values of the input beams (or far-field angle) are $13^\circ \times 13^\circ$ and $25^\circ \times 25^\circ$, respectively. When FWHM value of the input beam is large, the spectral broadening appears mainly in wavelengths less than λ_p and

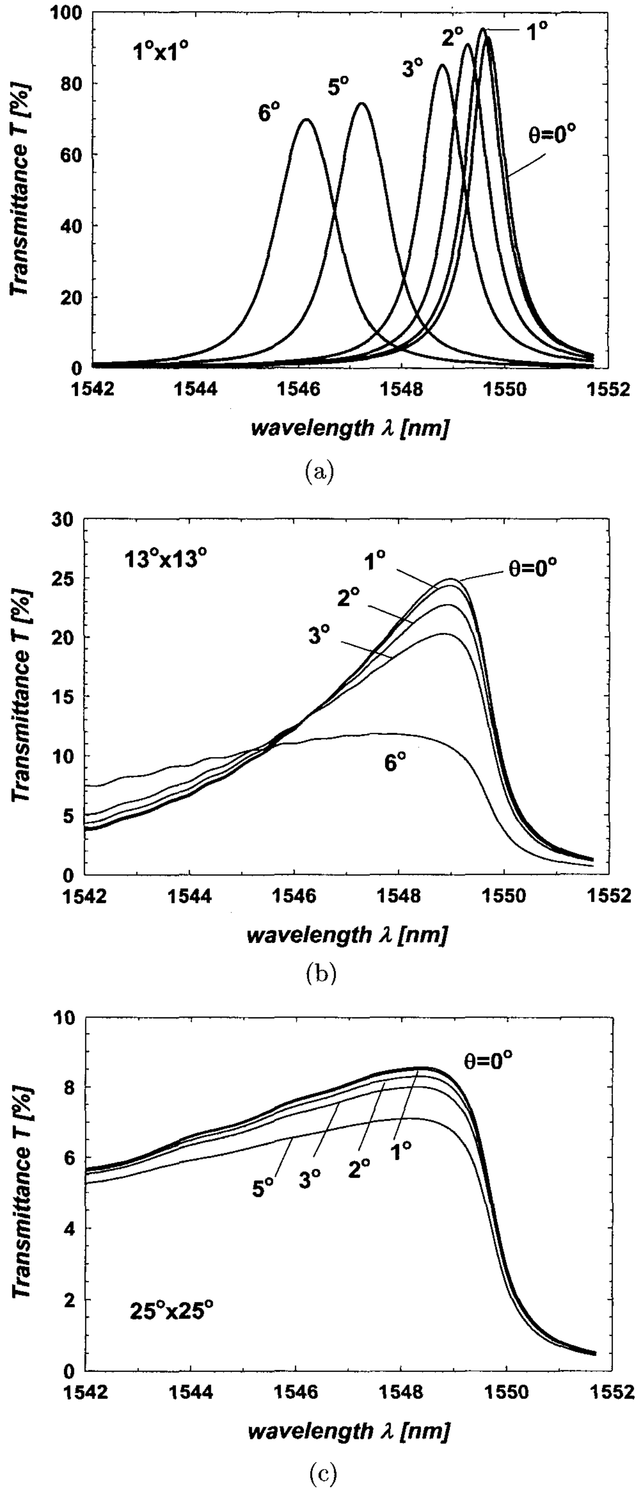


FIG. 2. Calculated transmission spectra of an etalon for several angles of incidence. The full-width at a half maximum (FWHM) value in far-field pattern (FFP) of an input beam is assumed as (a) $1^\circ \times 1^\circ$, (b) $13^\circ \times 13^\circ$, and (c) $25^\circ \times 25^\circ$.

the spectrum becomes asymmetric for all values in the range of θ. However, the λ_p does not shift considerably with θ and the maximum transmittance T_{max}

decreases compared to the plane wave input case. These can be explained by the following two factors. Firstly, when the plane wave is obliquely incident on an etalon, the transmittance spectrum is broadened in shorter wavelengths and T_{max} becomes small. Secondly, an input light with a finite spot-size consists of plane waves with different wave vectors and amplitudes, and the transmittance of a spatially confined input beam can be considered as the sum of asymmetrically broadened line shapes.

According to the results in Fig. 2 (b), even though the spectrum is broadened for an input beam with a finite spot-size, it is noticeable that the slopes of the transmittance curves in longer wavelengths than λ_p are not changed significantly even for different θ values. Furthermore, the magnitudes of slopes are enough to discriminate the wavelength drift of the laser. This suggests that a wavelength locker can be made without collimation lens and with a large alignment tolerance. Therefore, it is possible to implement a wavelength locker using only the passive alignment technique if the FFP of laser output were as narrow as about $10^\circ \times 10^\circ$. This implementation can reduce the packaging cost significantly.

Our analysis is mainly based on the plane wave decomposition of the input beam and the application of Fresnel's law [4,5]. The details of the modeling and calculation for various input beams can be found elsewhere [6].

III. FABRICATIONS AND RESULTS

To fabricate an internal wavelength locker, an EML chip was bonded to the ceramic sub-mount. For obtaining partially collimated beam, the emitted beam from the rear side of the DFB laser was partially collimated down to about $10^\circ \times 10^\circ$ by an aspherical lens with effective numerical aperture (NA) of 0.55. The aspherical lens was AR coated on both sides at 1550 nm bands. The average backward output power of the EML device is about 1.5 mW or less because of the high-reflection (HR) coating on the rear facet for high modulated output power on the front facet. The collimating lens covered with metal (KOVAR)-based lens-holder was fixed to the metal (KOVAR) base by laser welding. As a next step, two photodiodes and a beam splitter (2 mm×2 mm×0.5 mm), if necessary, were passively mounted on a marked ground on the metal base by Pb-Sn soldering. The incidence angle to the photo diodes should have some offsets to the normal angles to prevent undesired optical feedbacks. The splitting ratio of the beam splitter can easily be controlled by optical coating, and we used the ratio of 80 : 20 (wavelength PD : power monitor PD) at 45° to get enough photo-current level in the wavelength PD. Finally, an FP etalon filter (1.5 mm×1.5 mm×0.8 mm and finesse of ~ 6) was mounted on a rotatory metal housing by In-Sn soldering and the filter assembly was fixed by 2-point YAG laser-welding. The last of the packaging procedures are exactly the same as those of conventional DFB laser or EML modules.

Fig. 3 shows the wavelength locking characteristics of 10 Gbps EML module fabricated in our experiment with the internal wavelength locker using divergent beam. The wavelength locking curve was obtained by changing the TEC temperature of an EML module. Typically an EML device has a temperature dependent wavelength shift of about 0.1 nm/℃. The wavelength shift causes a remarkable change in the photocurrent values of a wavelength PD. However, the photocurrent values of a power monitor PD have small or no changes. The lasing wavelength of the EML is 1546.12 nm at the driving current of 75 mA and the temperature of 24.6℃, which is the wavelength locking point. The currents of monitor PD and wavelength PD are 42.0 μA and 9.2 μA at the locking point, respectively. In this scheme, we could easily get wavelength locking with a relatively simple optical scheme, however, the wavelength PD value was very low. It was because we used a divergent beam without any collimation, so the transmittance was also quite low at the locking point. Additionally, the output power from the rear facet of the 10 Gbps EML was as low as about 1.5 mW. Even though the wavelength PD value was very low, we could find that this scheme worked well as an internal wavelength locker. If we can adapt a spot-size converter in the rear side of the EML device or increase the output power from the rear facet of an EML, the photocurrent value of the wavelength PD will increase up to an acceptable value (at least 20 μA).

Fig. 4 shows the wavelength locking characteristics of the 10 Gbps EML module also fabricated in our

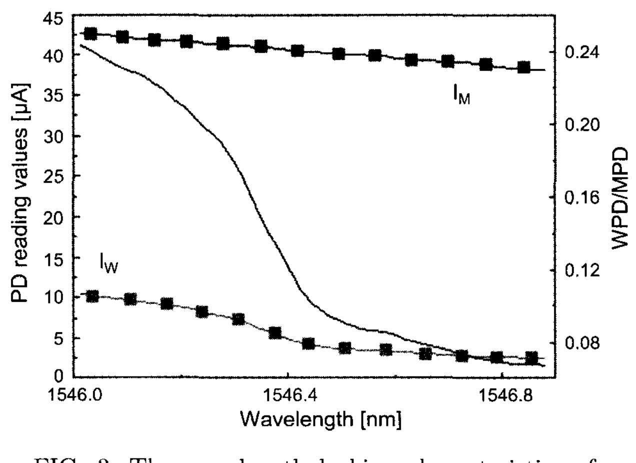


FIG. 3. The wavelength locking characteristics of an internal wavelength locker integrated 10 Gbps EML module using divergent beam.

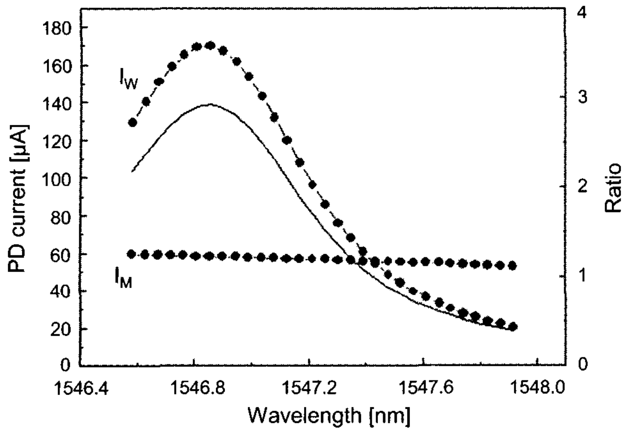


FIG. 4. The wavelength locking characteristics of an internal wavelength locker integrated 10 Gbps EML module using partially collimated beam.

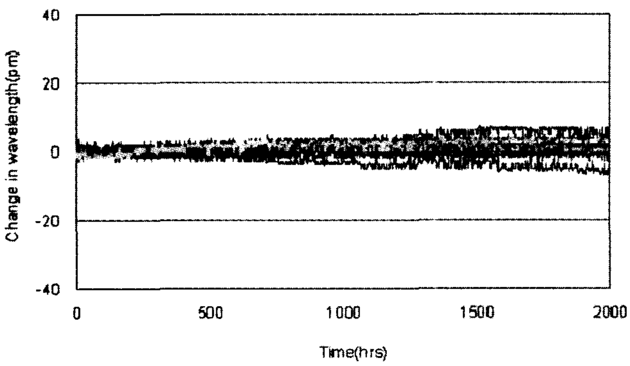


FIG. 5. The wavelength aging characteristics of internal wavelength locker integrated 10 Gbps EML module using partially collimated beam.

experiment with internal wavelength locker using partially collimated beam. The lasing wavelength of an EML is 1547.32 nm at the driving current of 75 mA and the temperature of 23.2℃, which is the wavelength locking point. The currents of monitor PD and wavelength PD are 56.0 μA and 71.7 μA respectively at the locking point. The estimated filter slope is about 0.177 μA/pm and the capture range is more than 45 GHz. We could get relatively wide capture range by lowering the filter slope (finesse of $\sim$ 6) while maintaining relatively high transmittance of a filter.

Fig. 5 shows the accelerated wavelength aging results of 10 Gbps EML modules with integrated internal wavelength lockers using partially collimated beams over 2000 hours. The EML modules were loaded in a hot chamber (70℃) and were connected to the wavelength locking and APC driving circuitry. The wavelength drifts over time were monitored during continuous wave (CW)-mode operation. The average wavelength drift of 10 modules was measured to be about $\pm$ 5 pm or less during 2000 hours, which was far better than the specification. As a reference, our previous result without internal wavelength locker showed the wavelength drift of about $\pm$ 10 pm or more during 2000 hours. Therefore, we think, these modules can successfully be applicable as sources for 50 GHz channel spacing dense WDM applications and even for 25 GHz channel spacing dense WDM applications.

IV. CONCLUSIONS

We have successfully fabricated and demonstrated the internal wavelength locker for dense WDM sources by adapting a simple and robust optical scheme and fabrication method in 10 Gbps EML modules. These wavelength lockers showed wide capture ranges with high photocurrent levels. The wavelength aging result shows very small wavelength drift. These modules, we think, can be applicable to the 50 GHz channel spacing dense WDM applications.

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