doi:10.3788/gzxb20144307.0706001

Analysis of Center Wavelength Shift of VCSEL Light in AWG for WDM-PON Applications

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Abstract: Center wavelength shift of vertical cavity surface emitting laser light in arrayed waveguide gratings is verified with mathematical and experimental analysis. It is induced by the linearly increasing trend of optical power of vertical cavity surface emitting laser by bias current increase. It is retrieved effectively to the original center wavelength by simple correction method of compensation. This was done for application of vertical cavity surface emitting laser as a light source in optical line terminal of wavelength division multiplexing-passive optical network.

Key words: Wavelength control; Optical Line Terminal (OLT); Wavelength-Division-Multiplexing Passive Optical Network (WDMPON); Vertical Cavity Surface Emitting Laser (VCSEL); Wavelength shift; Compensation

OCIS Codes: 060.0060; 060.2630; 060.3735 **文章编号**:1004-4213(2014)07-0706001-4

0 Introduction

Even though Wavelength Division Multiplexing - Passive Optical Network (WDM-PON) technology has outstanding performance, its high cost of Capital Expenditure (CapEx) and Operating Expenses (OpEx) has weakened its wide commercialization.

Vertical Surface Cavity Emitting Laser (VSCEL) has been studied as a light source for cost-effective economic Optical Line Terminal (OLT) of WDM-PON system[1-2]. Though VCSEL has competitiveness in cost, it has showed issues to overcome such as wavelength chirp and dispersion to be applied as a light source for long-haul optical transmission[3]. However the most important factor to consider with VCSEL for WDM-PON application is a precise wavelength control. An automatic wavelength control method using Rayleigh backscattering has been introduced[4]. J H moon, et al. introduced an automatic wavelength control method of a tunable laser using a spectrum sliced low-power Broadband Light Source (BLS)[5]. Fixing the wavelength of VCSEL light is a key control factor especially for Dense Wavelength Division-Multiplexing (DWDM) application.

In controlling the wavelength of VCSEL light to be positioned at the center wavelength in a channel of an Arrayed Waveguide Gratings (AWG), the position of center wavelength shifts from that measured using BLS which is designed to be matched with ITU-T DWDM wavelength grid[6]. For some VCSELs, the degree of wavelength shift is more than 10% of 0.8 nm of channel spacing of center wavelengths for DWDM system. This shift should be corrected since it can increase the inter-channel crosstalk of DWDM system, working as a source of signal quality degradation. This shift is originated from the linearly changing tendency of optical power and wavelength of VCSEL light by supplied bias current change.

In this study, we investigate the center wavelength shift of VCSEL in mathematical manner and verify it with the measured results. A simple correction method by compensation to retrieve the wavelength shift is suggested for the precise control of wavelength of VCSEL.

1 Wavelength control scheme with VCSEL

Fig. 1 shows a block diagram for wavelength control scheme of N-channel transmitter with VCSELs for OLT in WDM-PON system. 10% of optical power at common port of AWG is split to a monitoring section for the wavelength control. The monitoring section is composed with monitoring AWG (mAWG) and monitoring Photo Detectors (mPDs). The mAWG has identical optical characteristic with AWG so that the

Foundation item: The Korea Communications Commissions, Government Funded Project (Low-cost and high-capacity NG-PON2 core technology for next generation multi-service applicable access platform)

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Received: Oct. 22, 2013; **Accepted**: Feb. 14, 2014

center wavelength and loss profile of each channel should be exactly matched. The photocurrent generated by the mPD shows the highest value at the center wavelength position in AWG. With the photocurrent output, the center wavelength of the VCSEL light can be searched by controlling the bias current to the VCSEL and the temperature of thermo-electric cooler (TEC) on which the VCSEL is set. We fixed the TEC temperature and used the bias current to control the wavelength of VCSEL light. This control is done in the control part.

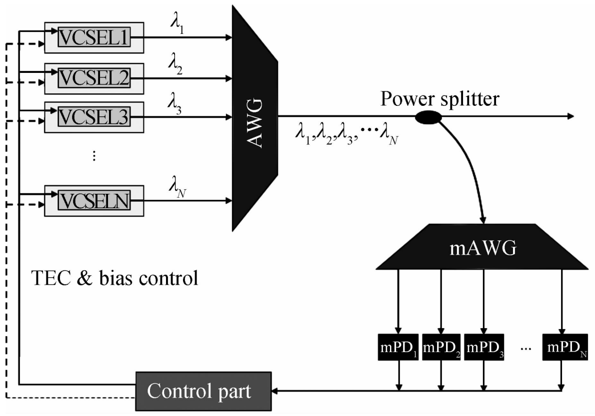

Fig. 1 Block diagram of wavelength control scheme with VCSEL for OLT in WDM-PON

2 Mathematical analysis

Both the optical power and the wavelength of VCSEL change simultaneously by bias current, which causes the center wavelength position in AWG is shifted. The shift is slanted toward higher-wavelength side due to the linearly increasing characteristic of optical power by bias current increase within 2 mA of working range. This phenomenon is well described in Fig. 2. The sloped upper line is an optical power line of

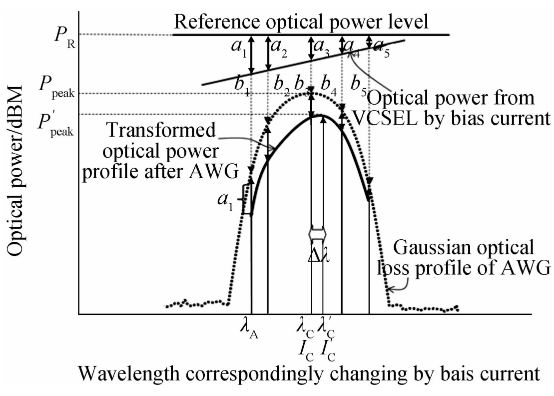

Fig. 2 Center wavelength shift of VCSEL in AWG

VCSEL linearly increasing as bias current increases. Within working bias current range of less than 2 mA, the equation of trend line of optical power by bias current can be given as a line equation as below Eq. (1).

$$P_o=\delta x+\varepsilon \tag{1}$$

Where, δ and ε are constants indicating the slope and intercept of the trend line respectively. The constant δ can have a unit of dBm/nm or dBm/mA. That is, it is dependent on the wavelength which is equally dependent on the bias current.

The dotted curve is a Gaussian optical loss profile (L_o) of AWG channel. It can be written as a following Eq. (2).

$$L_o=\alpha e^{-(x-\beta)^2/2\gamma^2} \tag{2}$$

Where, α, β, and γ are constants decided by Gaussian profile shape. The variable x means wavelength or bias current in this equation. The upper horizontal line is an ideal reference optical power level (P_R), which has hypothetically same level of optical power by changing bias current. With the ideal reference optical power level, the optical power passing out the AWG channel shows Gaussian profile with peak power of P_{peak} at the center wavelength λ_C with a bias current of I_C.

However, in real working situation, the optical power of VCSEL increases by bias current increase within working range. This makes the optical power passing out of the AWG channel have transformed profile with a new peak optical power of P'_{peak} The center wavelength in which the optical loss is the least within AWG loss profile is shifted to λ'_C with a shifted bias current of I'_C

If we assume that the difference between reference power and real power at arbitrary wavelength λ_A is a_1, the optical power after the AWG is decreased by a_1 from the Gaussian loss value at the wavelength λ_A. By applying this to every point of wavelength, the transformed optical power profile can be obtained. The equation of transformed profile, P_1, can be written as a following Eq. (3).

$$P_1=\delta x+\varepsilon\alpha e^{-(x-\beta)^2/2\gamma^2} \tag{3}$$

By differentiating the Eq. (2) with variable x, and making it equal to zero as shown below relation Eq. (4), the optimal bias current value x for center wavelength of Gaussian loss profile of AWG can be obtained.

$$dL_o/dx=d[\alpha e^{-(x-\beta)^2/2\gamma^2}]/dx=0 \tag{4}$$

In the same way, the optical power equation after AWG, Eq. (3), can be differentiated and written as below Eq. (5) to find the optimal bias current for center wavelength of transformed optical power profile.

$$\delta-d[\alpha e^{-(x-\beta)^2/2\gamma^2}]/dx=0 \tag{5}$$

If we let the optimal current difference between the x values satisfying Eq. (4), and (5) is $\Delta\varphi$[mA], then, the center wavelength shift ($\Delta\lambda$) can be written as a simple Eq. (6) considering the average wavelength change by bias current of VCSEL, ρ[nm/mA].

$$\Delta\lambda=\rho\Delta\varphi \tag{6}$$

3 Experimentals

The center wavelength shift phenomenon of VCSEL in AWG was experimentally verified. Fig. 3 shows an experimental set-up for test. Two VCSELs of A (L-band), and B (C-band) of Transmitter Optical Sub-Assembly (TOSA) were used as light sources. The TEC controller kept the temperature of the VCSEL A with 65 ℃, and the VCSEL B with 25 ℃. The wavelength and power of the optical output from the AWG was detected using an Optical Spectrum Analyzer (OSA) and a wavelength meter selectively using an optical switch. The AWG has a specification of 32-ch, cyclic, 100 GHz spacing, athermal with SC/APC connectors, and C + L + S2 bands. The athermal specification of AWG is essential prevent thermal effect to the wavelength in AWG.

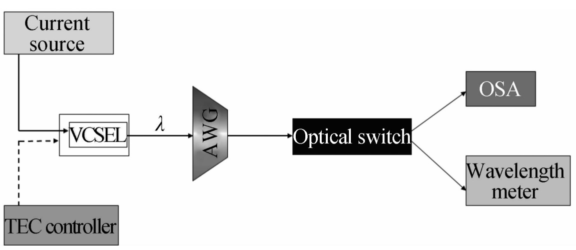

Fig. 3 Experimental set-up for the measurement of center wavelength shift in AWG

Fig. 4 shows I-L-W plots of two VESELs. The bias current to VCSEL A was supplied from 8 mA to 10 mA, and to VCSEL B from 6 mA to 8 mA with 0.01 mA of step increase. For the VSCEL A, the slopes of optical power, and wavelength are 0.78 dBm/mA, and 0.31 nm/mA. Those of the VCSEL B are 0.25 dBm/mA, and 0.69 nm/mA (δ).

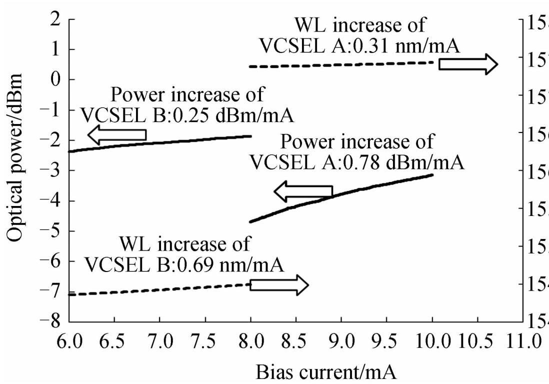

Fig. 4 Plot of optical power and wavelength by bias current (I-L-W) of two VCSELS, VCSELs A, and B

Fig. 5 shows two normalized Gaussian optical loss profiles of L-band, and C-band channels of AWG, measured using BLS sources. The average optical power linear increase by wavelength of VCSELs A, and B are described with lines. The center wavelengths of two channels of AWG are 1 574.073 nm for L-band, and 1 544.450 nm for C-band respectively. The optical powers for VCSELs A, and B increased by 2.51 dBm/nm, and 0.36dBm/nm by wavelength respectively.

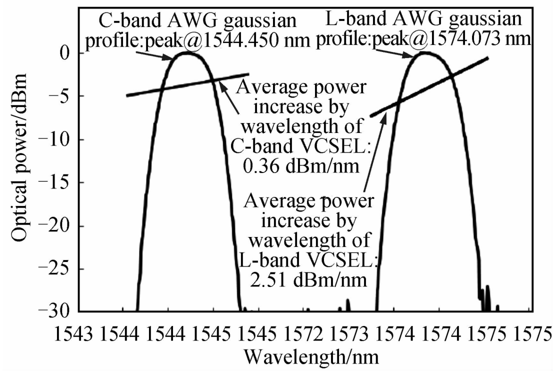

Fig. 5 Measured Gaussian optical loss profile of C-band, and L-band channels of AWG, and average power increase by wavelength of VCSELs A, and B

The measured center wavelength position of the VCSEL A, which has a higher power increase by wavelength of 2.51 dBm/nm, is shifted around 0.088 nm from 1 574.073 nm to 1 574.161 nm. Fig. 6 shows a measured optical power profile of VCSEL A connected with the L-band channel of AWG. In Fig. 6, larger dependency of optical output power by bias current of VCSEL A shows considerable center wavelength shift in AWG channel.

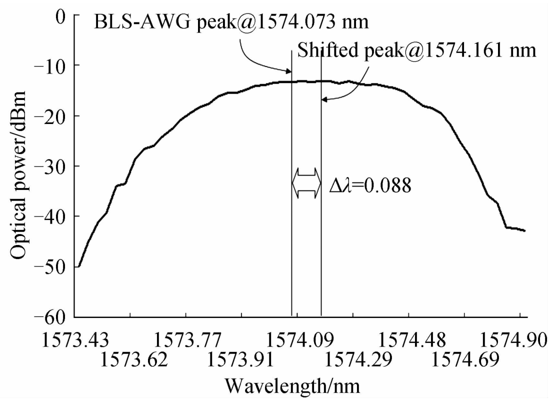

Fig. 6 Measured optical power profile of VCSEL A connected with L-band channel of AWG

The 0.088 nm of wavelength shift is quite large to be more than 10% of the channel spacing of 0.8 nm in DWDM. It is also larger than the ITU recommended range of wavelength accuracy of for 8-channel DWDM[6]. In contrast, the VCSEL B shows unchanged value of 1 544.450 nm. The less power increase by wavelength of 0.36 dB/nm, and by bias current of 0.25 dBm/mA of VCSEL B is attributed to this unchanged center wavelength.

4 Correction of the wavelength shift

The center wavelength shift of VCSEL light in AWG should be corrected. The correction can improve the signal integrity by decreasing the crosstalk and Bit Error Rate (BER)[7]. Correction of the center wavelength shift is done by deducting the of trend line of VCSEL A from the transformed optical power profile at each bias current point, which is numerically expressed as Eq. (3), $P_1 = \delta x + \varepsilon - \alpha e^{-(x-\beta)^2/\gamma^2}$. The corrected center wavelength shows 1 574.062 as shown in Fig. 7. In Fig. 7, by simply deducting the measured optical power trend line, 0.78x, from the transformed optical power profile, the correction can be achieved. The corrected center wavelength 1 574.062 nm is well matches with that measured by BLS, 1 574.073 nm. Optical power decrease by correction is negligible with 0.37 dB. The difference of 0.011 nm from the BLS-AWG center wavelength is within the ITU grid wavelength accuracy range of worst case $N = 4^6$. For the VCSEL B, correction by deducting 0.25x is negligible with 0.008 nm change.

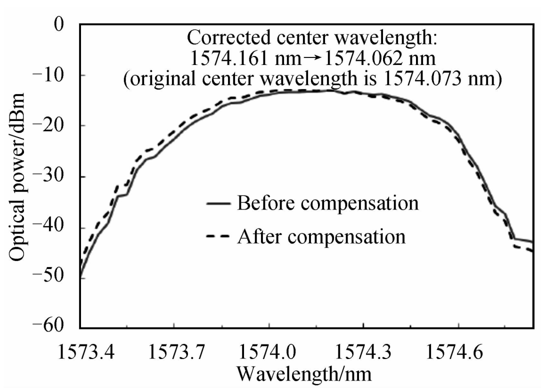

Fig. 7 Correction of the 0.08 nm of center wavelength shift of VCSEL A

5 Conclusion

The center wavelength shift phenomenon of VCSEL light in AWG is verified for the application of OLT in WDM-PON system. It is induced from the bias current dependency of optical power of VCSEL. Simple correction method is accomplished by deducting the power of measured trend line from the shifted optical power profile.

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