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External-Fiber-Grating Vertical-Cavity Surface-Emitting Lasers

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***Abstract*—A Bragg grating in graded-index multimode fiber was coupled to a 0.8-μm VCSEL. By using a fiber Bragg grating, the spectral width of the VCSEL decreased to 1/2–1/3 of the initial value, depending on the temperature of the fiber Bragg grating. The minimum spectral width was less than 0.1 nm FWHM. Data transmission using 1-km graded-index multimode fiber was investigated at 700 Mb/s. The power penalty decreased by using the fiber Bragg grating. The decrease was 2 dB for the optimum grating temperature at a bit error rate of 10^{-9}.**

***Index Terms*—Fiber grating, multimode fiber, optical fiber communication, surface-emitting laser.**

I. Introduction

VERTICAL-CAVITY surface-emitting lasers (VCSELs) have merits over conventional edge-emitting diode lasers in circular output beams and easy coupling with fibers, especially with multimode fibers. They have wide application in parallel interconnects and local area networks. However, there have been few studies on spectral control using an external tuning device. Although wavelength tuning of a VCSEL has been performed using a micromechanical mirror [1], spectral narrowing using an external optical element has not been reported. As a VCSEL has a short cavity of the order of micrometers, it oscillates in the single longitudinal mode. However, the typical spectral width is several hundred picometers, which is much larger than that of the single-longitudinal-mode edge-emitting diode lasers or fiber lasers. If the spectral narrowing is possible, transmission capacity of communication systems will increase.

On the other hand, fiber Bragg gratings (FBGs) have been used for tuning elements of diode lasers and fiber lasers [2]. FBG-tuned diode lasers are especially expected as light sources for wavelength-division multiplexing systems [3]. In these studies, however, FBGs have been formed only in single mode fibers. FBGs in multimode graded-index fiber were first proposed by Wanser *et al.* [4], and experimentally studied by the present authors [5]. As multimode fiber has a large core diameter, multimode FBG's have an advantage of easy coupling with various lasers including a $Cr^{3+}:LiSrAlF_6$ laser [6], [7]. They will also be suitable for tuning of a VCSEL, because a VCSEL for optical communication has a relatively large emitting area.

As an alternative method, the modal dispersion can be reduced by butt coupling with a VCSEL with a small emitting area of less than ten micrometers, and a 3-Gb/s 500-m multimode-fiber transmission has been reported [8]. However, a critical alignment will be required to couple the fibers. It is desirable that simple lens coupling is available.

In this letter, we perform spectral narrowing of a VCSEL using simple lens coupling with a FBG. Characteristics of the FBG-coupled VCSEL are investigated for 1-km multimode graded-index fiber transmission.

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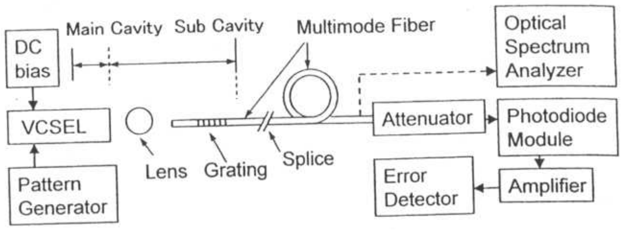

Fig. 1. Experimental setup of a VCSEL coupled with a multimode fiber Bragg grating and multimode-fiber transmission.

II. Experiment

Fig. 1 shows the experimental setup consisting of a transmitter using a VCSEL and a multimode FBG as a subcavity, transmitting multimode fiber, and a receiver. The signal source was a Tektronix CSA907 random pattern generator. The receiver consists of a Hamamatsu S7472 photodiode module, a 24-dB amplifier, and an error detector. Spectral measurements were performed with an optical spectrum analyzer of 0.1-nm resolution.

The FBGs were fabricated using a KrF excimer laser by the two-beam interference method [5] that is suitable for adjusting the Bragg wavelength to the VCSEL wavelength. The optical fiber was standard graded-index multimode fiber with a core diameter of 50 μm and a numerical aperture of 0.2 loaded with 120-atm hydrogen for a week. The laser irradiation was performed for 10 min with an energy density of 0.07 J/cm^2 and a repetition rate of 10 Hz. A typical transmission spectrum of the FBG is shown in Fig. 2. The maximum reflectivity was 38%. The spectral width of reflection was 6.5–nm full-width at half-maximum (FWHM).

The VCSEL was Mitel 1A444 designed for data communication. The typical oscillation wavelength is 840 nm, the typical spectral width is 0.5 nm FWHM, and the 3-dB bandwidth is 2

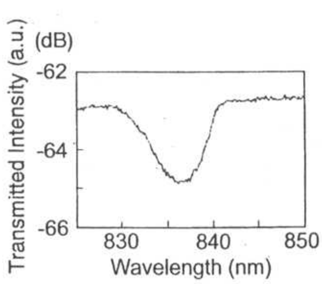

Fig. 2. Transmission spectrum of a fiber Bragg grating in multimode fiber.

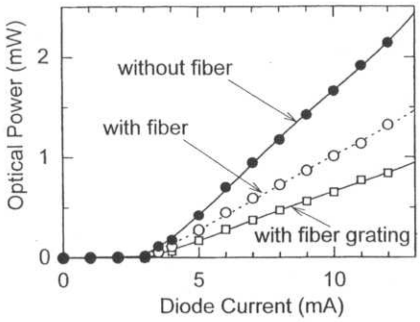

Fig. 3. Output power of a VCSEL, fiber-coupled power, and grating-tuned fiber output as a function of the diode current.

GHz. The size of emitting area is 25 μmϕ. The VCSEL is in a package with a lens window. The distance between the FBG and the VCSEL was 15 cm in air-equivalence except transmission experiments. Fig. 3 shows the measured powers without fiber, with fiber, and with a FBG. At $I = 12$ mA, the laser power without fiber was 2.1 mW, and the fiber-coupled power was 1.3 mW; therefore, the coupling efficiency was 62%. By coupling a FBG, the fiber output power decreased by 2 dB as the power at $I = 12$ mA was 0.8 mW. The threshold current (3.5 mA) did not change after using a FBG, and the reason is not clear. It may be due to a high reflectivity of the DBR mirror of the VCSEL.

Next, we measured the oscillation spectrum of the VCSEL with a FBG without modulation. Fig. 4 shows the spectral widths and the center wavelengths with and without the FBG. The spectral width decreased for any diode current. Especially, at $I = 6$ mA, the spectral width decreased from 0.29 to 0.13 nm FWHM, which is 45% of the initial value. The VCSEL had a red shift by 0.6 nm for increase in I from 3.5 to 12 mA. The red shift is mainly due to the increase in the refractive index with the temperature. With a FBG, the wavelength shifted toward the center Bragg wavelength of 836.5 nm by 0.2 and 0.05 nm for $I = 9$ and 12 mA, respectively.

Next, we varied the temperature of the FBG using a Peltier heat pump. The spectral width for $I = 12$ mA varied between 0.1 and 0.17 nm FWHM as shown in Fig. 5, and the variation was almost periodic. The minimum spectral width of 0.1 nm FWHM, the resolution limit of the measurement, was obtained at 5.1 °C.

For transmission experiments, a FBG was spliced with a 1-km multimode graded-index fiber with a core diameter of 50 μm with a bandwidth of 500 MHz·km. A digital signal voltage was applied to the VCSEL. The dc bias voltage was 1.7 V, just above the threshold. The data pattern was $2^{23} - 1$ PRBS (psuedo-random pattern bit sequence) and the data rate was 700 Mb/s, the

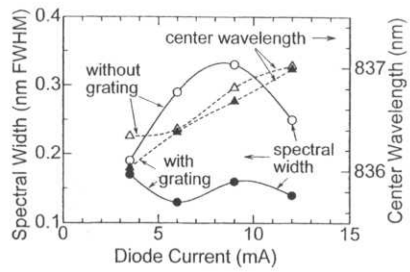

Fig. 4. Measured results of the spectral width of and the center wavelength of a grating-tuned VCSEL without modulation as a function of the diode current.

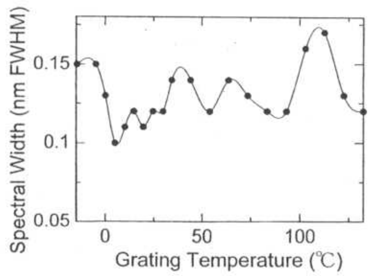

Fig. 5. Dependence of spectral width of a grating-tuned VCSEL without modulation on grating temperature.

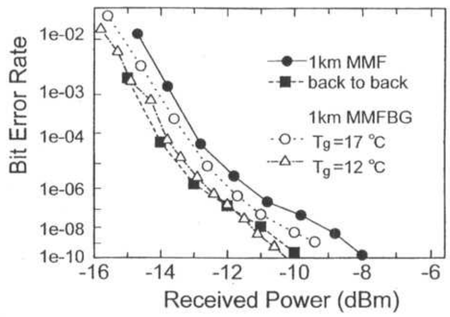

Fig. 6. Characteristics of a 700 Mb/s multimode-fiber transmission system using a VCSEL coupled with a fiber Bragg grating.

maximum rate of the pattern generator. The total cavity length including the length of the FBG (6 mm) was about 3 cm in air-equivalence, which should be small enough for sub-Gb/s modulation [3]. Fig. 6 shows the measured results of the bit error rate (BER) for transmission by 1-km multimode fiber with and without a FBG and the back-to-back measurement, comparing two different grating temperatures of 12 °Cand 17 °C. These temperatures approximately correspond to the best and the worst case, respectively. The power penalty without a FBG was 2 dB. The power penalty decreased at all the BER range by using a FBG. For the optimized grating temperature of 12 °C, the power penalty at a BER of 10^{-9} decreased by 2 dB. For an unoptimized grating temperature (17 °C), the power penalty was 1 dB, which is half of that without a FBG. As there is a power loss of 2 dB by using a FBG, it would be necessary to optimize the grating reflectivity.

III. Discussion

The Bragg reflection condition of a FBG with a period Λ is given by $\beta = \pi/\Lambda$, where β is the propagation constant. In multimode fibers, a group of modes having the same propagation

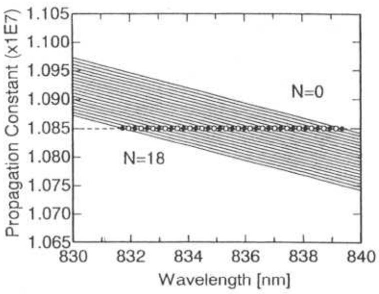

Fig. 7. Theoretical propagation constants, principal modes, and Bragg wavelengths (•: from N to N reflection, o: from N to $N \pm 1$ reflection) [5].

constant can be represented by a principal mode [5]. The propagation constant for the Nth principal mode in graded-index fiber is approximated by

$$\beta = \frac{2\pi}{\lambda} n_1 \sqrt{1 - 4\Delta \frac{N+1}{V}} \tag{1}$$

where Δ is the maximum relative index difference and V is the normalized frequency. Fig. 7 shows the propagation constants given by (1) at around 840 nm. 19 principal modes exist, and the cross points with π/Λ correspond to the Bragg wavelengths. The Bragg wavelengths are in the range of 7.7 nm, which is near the experimental value (6.5 nm FWHM). In our previous measurement on a 1.55-μm FBG [5], the number of reflection peaks was approximately twice the number of principal modes, which was due to the reflection from N to $N \pm 1$ mode. So that, in the present experiment also, the number of reflection peaks is about two times (37) as shown in Fig. 7, and the separation is 0.21 nm. The temperature dependence of each reflection peak is calculated as 8.5 pm/°C, almost the same with single-mode FBGs [5].

In spite of the wide reflection spectrum of the multimode FBG of 6.5-nm FWHM, spectral narrowing has been demonstrated. This is because both the effective spectral width and the reflectivity of a multimode FBG depend on the mode excitation condition and that the reflectivity may exceed 90% for few-mode excitation [5]. It is considered that the laser oscillation grows up only for a few of propagating modes in fiber and thus a narrow oscillation spectrum is obtained. For variation in the grating temperature (Fig. 5), the difference between the wavelength of the gain maximum of the VCSEL and the nearest reflection peak also varies. If they agree each other, the lasing spectrum will be narrower, and if they are different, the spectrum will be wider. The temperatures corresponding to two neighboring peaks (0.21 nm apart) is calculated to be 25 °C apart, which is near the temperature period in Fig. 5. Variation in the transmission characteristics with the grating temperature can also be explained by the same mechanism: agreement between one of the reflection peaks of the FBG and the center wavelength of the VCSEL. It is noted that the optimum grating temperature will depend on the operating conditions of a VCSEL, because the center wavelength of a VCSEL depends on the current and the package temperature. The effect of longitudinal modes of the subcavity is considered to be small, because the mode separation is 2.3 pm for the cavity length of 15 cm in air-equivalence, which is two orders of magnitude smaller than the separation of neighboring modes (0.21 nm).

The mechanism of reduction in the power penalty may not be simple. The first mechanism is reduction in the wavelength dispersion by spectral narrowing. The second mechanism will be reduction in the modal dispersion because limited propagation modes are oscillating. Further study on near-field or far-field patterns may be necessary. The effect of mechanical misalignment should also be studied further.

IV. Conclusion

Spectral narrowing of a VCSEL has been demonstrated by using a FBG in multimode fiber. The spectral width decreased to one third or half of the initial value, and the minimum value was the resolution limit of 0.1-nm FWHM after using temperature control. The power penalty decreased up to 2 dB by using a FBG at an optimum temperature. A fiber-grating-tuned VCSEL will be useful for high-bit-rate parallel transmission systems and local area networks.

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