Ultrashort Optical Pulse Transmission Characteristics of Vertically Coupled Microring Resonator Add/Drop Filter

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Abstract—The ultrashort optical pulse transmission characteristics of a vertically coupled microring resonator (VCMRR) filter were measured at $1.55\mu\text{m}$ wavelength, and the transmission capacity per channel was evaluated. The pulsewidth at the output was measured to be 3.4 ps, when 1.2 ps input pulse with a sech pulse shape from a fiber laser was incident on the microring resonator filter with a fullwidth at half-maximum (FWHM) of 0.75 nm (94 GHz). From this result, the maximum transmission capacity of the filter was estimated to be approximately 50 Gb/s. The pulse broadening through the filter was theoretically analyzed, and it was confirmed that the pulse broadening evaluated from the bandwidth of the filter spectrum response were in good agreement with the measured results.

Index Terms—Add/drop filter, microring resonator, optical waveguide device, transmission capacity, transmission characteristics.

I. INTRODUCTION

MICRORING resonator devices are attractive as add/drop wavelength filters for wavelength multiplexed access networks, due to their functionality [1], [2] and compactness [3]. The ultracompact ring resonator can be realized by the high index contrast waveguide consisting of glass core and air cladding and the vertically coupled configuration [4], [5], where a microring resonator with a radius of a few tens of microns is stacked at the crossing point of cross-grid bus waveguides. Due to the stacked configuration, the upper and lower waveguides play different roles, i.e., the lower buried channel waveguides serve as input/output bus guides while the ring functions as the frequency selective element. In addition, the coupling strength between the ring and bus waveguides can be controlled more precisely than the lateral coupling, because the vertical separation is obtained by precisely controlling the deposition, rather than etching fine gaps. This allows us the fabrication of high Q micro-ring resonator filters with a

Fig. 1. Vertically coupled microring resonator add/drop filter.

very small radius of 10–20 μm , which exhibit bandwidths of 0.2–1.0 nm and a free spectral range (FSR) of 10–25 nm.

We have proposed and demonstrated a vertically coupled microring resonator (VCMRR) filter [5]–[10] as an add/drop filter for wavelength division multiplexed access networks. However, although the generalized dispersive properties of optical filters are analytically calculated [11], [12], there has been no detailed experimental or theoretical evaluation about the relationship between the bandwidth of the filter spectrum response and the maximum transmission capacity. In this study we measured the temporal transmission characteristics of a VCMRR filter using an ultrashort pulse from a fiber laser and evaluated the transmission capacity per channel. The relationship between the bandwidth of the filter and the output pulsewidth was analyzed using the Fourier transforms (FTs), and the theoretical results were compared with the experimental data.

II. VERTICALLY COUPLED MICRORING RESONATOR ADD/DROP FILTER

Fig. 1 shows the structure of the VCMRR filter. It consists of an input bus waveguide and an add/drop waveguide which are crossed at right angles. At the node, a ring waveguide, which serves as the wavelength selective crossconnect between the input and the corresponding add/drop waveguide, is placed on the crossed waveguides. To apply the ring resonator filter for WDM systems, a ring radius of a few micrometers is needed because the FSR of the filter is required to be a few tens of nanometers. Thus, the waveguide used for the VCMRR filter that we have proposed requires a high index contrast to reduce the bending loss caused by the small radius. In addition, the

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Fig. 2. Cross section of VCMRR filter used in the measurement.

Fig. 3. Spectrum response of VCMRR filter: (a) TE polarization and (b) TM polarization.

bus waveguide layer and the ring resonator layer can be optimized independently owing to the vertically coupled configuration. Fig. 2 shows the cross-sectional structure of the VCMRR filter used in the measurement. In this device, the ring and bus waveguide cores were formed of a compound glass with a composition of 17 mol% of Ta_2O_5 and 83 mol% SiO_2 , giving a refractive index of 1.6532 at $1.55 \mu\text{m}$ wavelength. The cladding and buffer layers were made of SiO_2 . The width and thickness of the bus waveguide are $2.0 \mu\text{m}$ and $0.5 \mu\text{m}$, respectively, and those of the ring waveguide are $1.5 \mu\text{m}$ and $1.5 \mu\text{m}$, respectively. The radius of the ring waveguide is $20 \mu\text{m}$. Details of the fabrication process were reported in [5].

The spectrum responses of the filter measured using a tunable LD are shown in Fig. 3(a) (TE polarization) and Fig. 3(b) (TM polarization). The spectrum response of the VCMRR filter

Fig. 4. Autocorrelation measurement of input pulse (3.19 ps/div).

is approximately expressed by a Lorentzian function, and the FWHM bandwidth for TE polarization was 0.75 nm (94 GHz) and that for TM polarization was 0.9 nm (112 GHz). This difference of spectral widths between TE and TM polarizations is caused by the difference of confinement factor between two polarizations.

Other polarization problems are the polarization dependence of resonant wavelength, PDL and PMD. The polarization dependence of resonant wavelength as seen in the [6] can be eliminated by a new polarization independent microring structure using the birefringent material as the overcladding, and this will be discussed in future. The difference of spectral width for TE and TM polarizations will also be improved by the polarization independent microring resonator. The PDL is small ($<1 \text{ dB}$) as shown in [6] and will be reduced further in the polarization independent device. The PMD, which is defined by the difference of pulse arrival time for TE and TM polarizations, will not occur in this device, because the optical path length is very short compared with the optical fiber.

III. ULTRASHORT OPTICAL PULSE TRANSMISSION CHARACTERISTICS OF FILTER

An ultrashort pulse train from a regeneratively modelocked fiber laser [13] with a $\text{sech}(at)$ pulse shape (a is a constant) was incident on the filter. The input pulse was linearly polarized, and the direction of polarization was controlled to be TE or TM polarization using a polarization maintaining fiber and a fiber rotation manipulator. The input pulse shape observed with an autocorrelator is shown in Fig. 4. The pulsewidth and the FWHM bandwidth of the input pulse are 1.2 ps and 2.1 nm , respectively. The wavelength was adjusted to a resonant wavelength of the filter, i.e., 1546.6 nm for TE and 1549.1 nm for TM. The output pulse shapes from the filter observed with the autocorrelator are shown in Fig. 5 for TE polarization and Fig. 6 for TM polarization. When the output pulse shape is assumed to be described by a $\text{sech}^2(at)$ function, the actual pulsewidth is 0.65 times the autocorrelation width. This results in an output pulsewidth of 3.4 ps for TE polarization. Similarly, the output pulsewidth for TM polarization was 2.8 ps . From these results, we can estimate the transmission capacity. As a pulse interval is typically set to be five to six times the output pulsewidth, the pulse interval in the present case is calculated to be 20 ps . This

Fig. 5. Autocorrelation measurement of output pulse: TE polarization (3.19 ps/div).

Fig. 6. Autocorrelation measurement of output pulse: TM polarization (3.19 ps/div).

corresponds to a transmission capacity per channel of 50 Gb/s. Thus this filter can be applied to 50 Gb/s transmission systems.

Although the maximum transmission capacity was confirmed to be about 50 Gb/s, the channel spacing in the WDM system is not determined by the bandwidth of the filter but the crosstalk characteristics. Since the Lorentzian response of single microring filter has large wings and the roll-off from the resonant to off-resonant state is very slow. This will be an obstacle to the dense WDM. This problem can be improved by higher order resonators [1] consisting of two or three coupled resonators and by the cascaded resonators [7].

Next, we observed the eye pattern from the VCMRR filter as shown in Fig. 7. The light source is the same fiber laser as used above, and the repetition rate, pulsewidth, and peak power are 10 Gb/s, 1.2 ps, and about 0 dBm, respectively. It is seen from Fig. 7 that the eye is clearly open. The bit error rate (BER) characteristic was measured by using the measurement system shown in Fig. 8. In this system, the insertion loss of the filter was compensated for by using erbium-doped fiber amplifiers (EDFAs). The insertion loss of the filter is about 25 dB [4], and this loss is mainly attributed to the input/output coupling loss caused by the large spot size mismatch between the busline waveguide ($\sim 2 \mu\text{m}$) and the fiber ($\sim 10 \mu\text{m}$), which is about 18 dB. This coupling loss to the fiber will be reduced by integrating the spot size transformer to match the spot size of input and output waveguides to that of the fiber. The measured BER characteristic is

Fig. 7. Measurement result of eye pattern (after filter).

Fig. 8. Measurement system for BER characteristics.

Fig. 9. BER characteristics.

shown in Fig. 9. In this figure, the back-to-back BER characteristic and the BER characteristic after the filter are shown by $\square$ and $\odot$, respectively. The power penalty was 0.5 dB, which is mainly attributed to the SNR of the EDFAs.

IV. THEORETICAL CONSIDERATION FOR TRANSMISSION CHARACTERISTICS

We analyzed theoretically the transmission characteristics of the VCMRR filter. First, we calculated the output pulsewidth from the filter bandwidth and the input pulsewidth by using FTs, and compared the calculated and measured results. Next, assuming that the output pulse shape was approximately expressed by an exponential or a sech-type function, the product of ΔT

and $\Delta\nu$ was calculated. Lastly, the calculated results were compared with the values of transform limited condition of exponential and sech functions, respectively.

A. Calculation Using the Fourier Transform

The input pulse shape from the fiber laser is given by

$$|f_{\text{in}}(t)|^2 \propto \text{sech}^2(at) \quad (1)$$

where $f_{\text{in}}(t)$ is the electric amplitude function, and a is a constant corresponding to the pulsedwidth. The spectrum response of the VCMRR filter is expressed by the Lorentzian function, given by

$$|H(\omega)|^2 \propto \frac{1}{1 + b^2(\omega - \omega_0)^2}. \quad (2)$$

The actual response measured by a spectrum analyzer and a tunable LD is given by $|H(\lambda)|^2$ as a function of wavelength λ . The calculation procedure is as follows.

First, the value of a corresponding to the input pulsedwidth is calculated from the measured pulsedwidth. $F_{\text{in}}(\omega)$ is the FT of $f_{\text{in}}(t)$. Next, the transfer function of the filter $H(\omega)$ is converted to $H(\lambda)$ using the relation $\omega = (2\pi c)/\lambda$, and the value of b which corresponds to the bandwidth of the spectrum response is calculated from the measured bandwidths. Finally, the FWHM of $|f_{\text{out}}(t)|^2$ is calculated by the inverse FT of the product $F_{\text{in}}(\omega)H(\omega)$, which is given by

$$f_{\text{out}}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F_{\text{in}}(\omega)H(\omega)e^{j\omega t} d\omega. \quad (3)$$

The value of the FWHM obtained above is the theoretical value of the output pulsedwidth.

First, the value of a in (1) is determined to be 1.47×10^{12} /s so that the input pulse expressed by (1) has a 1.2 ps pulsedwidth. The FT of $f_{\text{in}}(t)$ is given by

$$F_{\text{in}}(\omega) \propto \text{sech} \left[\frac{\pi(\omega - \omega_0)}{2a} \right]. \quad (4)$$

Next, the transfer function $|H(\omega)|^2$ given by (2) is expressed in terms of wavelength λ as

$$|H(\omega)|^2 = \frac{1}{1 + b^2(\omega - \omega_0)^2} = \frac{1}{1 + b^2 \left(\frac{2\pi c}{\lambda} - \frac{2\pi c}{\lambda_0} \right)^2} \quad (5)$$

and b is determined to be 3.39×10^{-12} s/rad for TE and 2.82×10^{-12} s/rad for TM so that the $|H(\lambda)|^2$ has a FWHM corresponding to the measured bandwidths of the filter (0.75 nm for TE and 0.9 nm for TM polarization). Substituting (4) and the following function in the angular frequency domain:

$$H(\omega) = \frac{e^{-j\frac{\omega n_{\text{eq}} 2\pi R}{c}}}{1 + jb(\omega - \omega_0)} \quad (6)$$

into (3), the output pulse shape $|f_{\text{out}}(t)|^2$ is obtained.

The calculated result is shown in Fig. 10, where the theoretical pulsedwidth is expressed as a function of the bandwidth of the filter. The calculated result is in good agreement with the

Fig. 10. Relationship between FWHM bandwidth of the filter and pulsedwidth of output signal.

measured results. Thus, it can be concluded that the pulsedwidth of output signal from the filter can be predicted by the FT, as long as the source wavelength is adjusted to the resonant wavelength of the filter.

B. Consideration on Output Pulse Waveform

If the input pulse with a 1.2 ps pulsedwidth (2.2 nm bandwidth) is approximated to be a δ function,

$$|F_{\text{out}}(\omega)|^2 \propto |H(\omega)|^2 \quad (7)$$

where $F_{\text{out}}(\omega)$ is the FT of $f_{\text{out}}(t)$, and an approximation of $|F_{\text{in}}(\omega)|^2 \simeq \text{const.}$ is used. Thus, the output spectrum is given by the filter response which is expressed by the Lorentzian function. The impulse response corresponding to the Lorentzian spectrum is

$$h(t) \propto \begin{cases} \exp(-\frac{t}{b}) & (t \geq 0) \\ 0 & (t < 0) \end{cases} \quad (8)$$

and the transform limited pulse expressed by (8) satisfies the following relation:

$$\Delta T \cdot \Delta\nu \simeq 0.11 \quad (9)$$

where ΔT and $\Delta\nu$ are the FWHMs of the intensity of pulse and the spectrum response, respectively.

On the other hand, we also consider the case when the input spectrum $F_{\text{in}}(\omega)$ is expressed by (4). We assume that the output spectrum is approximately

$$\begin{aligned} |F_{\text{out}}(\omega)|^2 &\propto \text{sech}^2 \left(\frac{\pi}{2a}(\omega - \omega_0) \right) \times \frac{1}{1 + b^2(\omega - \omega_0)^2} \\ &\cong \text{sech}^2 c(\omega - \omega_0) \left(c \simeq \left(\frac{\pi}{2a} \right)^2 + b^2 \right) \end{aligned} \quad (10)$$

that is, the output spectrum is expressed by the sech^2 function which has a narrower bandwidth than Fig. 3(a) and (b). Then the transform limited condition for the sech^2 pulse is given by

$$\Delta T \cdot \Delta\nu \simeq 0.32. \quad (11)$$

Now, we compare the measured results with the values given by (9) and (11). In this comparison, the FWHM of the spectrum

Fig. 11. Relationship between the pulsewidth and the bandwidth (transform limited pulse condition).

of the output pulse is smaller than the values shown in Fig. 3(a) and (b) which were measured using a CW tunable light source. This is because the spectrum responses shown in Fig. 3(a) and (b) correspond to the FT of the impulse response for which the light source has a very broad (white) spectrum bandwidth. When a sech^2 pulse light source with 1.2 ps pulsewidth was incident on the filter, the FWHM of the output spectrum was 0.55 nm for TE polarization, and 0.71 nm for TM polarization. Since the pulse shape was observed with an autocorrelator, when the pulse shape is assumed to be an exponential function corresponding to a Lorentzian spectrum, ΔT is given by 0.5 times the measured value with the autocorrelator as follows:

$$\Delta T = \frac{3.4 \text{ [ps]}}{0.65} \times 0.5 \simeq 2.62 \text{ [ps]} \quad (12)$$

for the TE polarization. Similarly, for the TM polarization, we have

$$\Delta T = 2.15 \text{ [ps]}. \quad (13)$$

Fig. 11 shows the relationship between the pulsewidth and the bandwidth assuming the exponential and the sech^2 output pulse shapes. In this figure, the measured values of the output pulse are also shown, by ■ and ● for the exponential pulse and by □ and ○ for the sech pulse shape. From Fig. 11, it can be seen that $\Delta T \cdot \Delta \nu$ of the actual output pulse has a value between the exponential pulse and the sech pulse. Thus, the actual output pulse has a shape in between the exponential function, which has broad pulse wings and the sech function which has lower wings.

V. CONCLUSION

We measured the ultrashort pulse transmission characteristics of a VCMRR filter. It was confirmed that the maximum transmission capacity per channel of the filter with FWHM of 0.75 nm (94 GHz) was approximately 50 Gb/s. The pulse broadening through the filter was theoretically analyzed using the FT, and it was shown that the pulsewidth can be accurately calculated from the spectrum response of the filter. Although the maximum transmission capacity was confirmed to be about 50 Gb/s, the channel spacing is not determined by the bandwidth of the filter but by the large wings of Lorentzian response. This problem

can be improved by incorporating higher order resonators [1] and cascaded microring resonators [7].

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