Electrically Tunable Delay Line Using an Optical Single-Side-Band Modulator

Tetsuya Kawanishi, Satoshi Oikawa, Kaoru Higuma, and Masayuki Izutsu

***Abstract* − The authors propose a tunable delay line using an optical single-side-band modulator and an optical fiber loop. The number of times light circulates in the loop can be controlled by the electric signal fed to the modulator. Packets of any lengths can go through the proposed delay line without any collisions, even if the length of the packet is larger than that of the delay loop.**

***Index Terms* − Delay line, optical modulation, single-side-band.**

I. Introduction

OPTICAL buffers that are composed of delay lines are key components in optical packet switching systems. To prevent packets from colliding, it is necessary to vary the delay at the buffer. There are two types of configurations for tunable optical delay lines [1]-[2]. One is comprised of an optical switch and a fiber loop, where the operation of the switch must be synchronized with the propagation cycle of the packet in the loop. The other consists of an array of several delay lines of various lengths connected to an optical switch by which we can select one from the array delay line. Each line has an optical amplifier and an optical switch, which results in a complicated setup. In this letter, we propose a novel electrically tunable delay line that has a simple setup. Oursystem consists of an optical single-side-band (SSB) modulator, a fiber Bragg grating (FBG), and an optical fiber loop. An optical amplifier is used to compensate for conversion loss at the modulator. The number of times a lightwave circulates in the loop depends on the frequency of the electric signal applied to the modulator. Thus, we can control the delay by switching the frequency without using delay lines of various lengths. In addition, it is not necessary to synchronize the switching timing with the cycle of the packet propagation.

II. Principle of Operation

Our system is comprised of a loop with an optical SSB modulator. As shown in Fig.1, the system has an optical port consisting of two optical circulators and an FBG placed between them. A lightwave whose optical frequency is out of the reflection band of the FBG can pass through the port, while a lightwave in the band cannot. Thus, an input lightwave whose frequency is out of the reflection band comes into the loop. When the modulator is not in operation, the lightwave goes through the loop once, and then it exits from the port. Consider that the SSB modulator is in operation and that the input optical frequency (f_0) is slightly lower than the edge of the reflection band, as shown in Fig. 2, where f_m denotes the frequency of the electric signal fed to the modulator and f_r is the reflection band width of the FBG. The input optical frequency can be shifted at the SSB modulator [3]-[5]. We assume that the dc-bias voltages for the modulator are tuned to generate the upper side-band. Of course, we can use the lower side-band instead of the upper side-band when f_0 is slightly higher than the upper edge of the reflection band. The f_0 lightwave, coming into the loop through the port, is input to the SSB modulator, and then its frequency is shifted to the reflection band ($f_0 + f_m$), Thus, the lightwave is reflected by the FBG and circulates in the loop again. During the successive circulation steps, the optical frequency is shifted at the modulator. After n times circulation, the frequency of the lightwave becomes $f_0 + nf_m$. We call such a spectral component an nth-order channel. After circulating several times, the lightwave exits the reflection band, where the number of circulation steps p is given by $pf_m > f_r > (p - 1) f_m$. In this letter, we call the spectral component of $f_0 + pf_m$ the prime channel, which is the lowest order channel in the channels whose frequency is higher than the reflection band. The output lightwave contains some other components resulting from the nonlinearity of the modulator and residual transmittance in the reflection

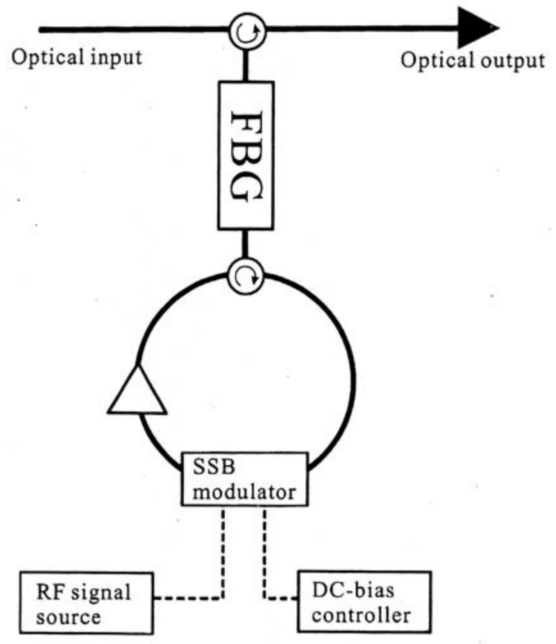

Fig. 1. Setup for our proposed delay line.

Manuscript received April 11, 2002; revised June 11, 2002.
T. Kawanishi and M. Izutsu are with Communications Research Laboratory, Koganei-si, Tokyo 184-8745, Japan (e-mail: kawanish@crl.go.jp).
S. Oikawa and K. Higuma are with the New Technology Research Laboratories, Sumitomo Osaka Cement, Chiba 274-8601, Japan.
Publisher Item Identifier 10.1109/LPT.2002.802387.

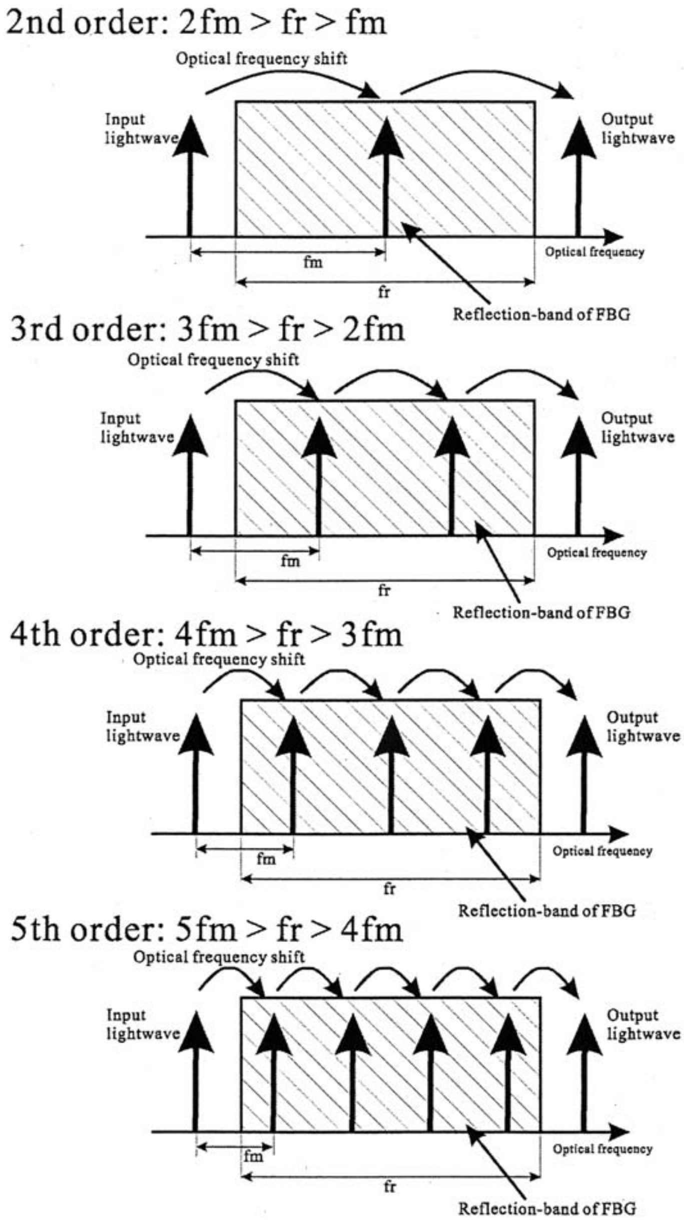

Fig. 2. Principle of the operation.

band. However, the prime channel would be dominant when we can consider that f_m is larger than the edge slope width of the reflection band, and that any high-order harmonic generation at the modulator is negligible. The propagation delay of a circulation step is given by $\tau = l/c$, where l denotes the effective optical length of the loop and c is the speed of light. The delay of the prime channel at the loop is dependent on f_m, as follows: $p\tau = \tau \times \mathrm{Int}(f_r/f_m)$, where $\mathrm{Int}(x)$ gives the smallest integer larger than x. Thus, we can change the delay $p\tau$ by switching the frequency of the electric signal f_m. The frequency can be switched at any time except when a packet is passing the SSB modulator, thus it is not necessary to synchronize the switching timing with the propagation cycle of the packet. In addition, we note that pulses longer than the optical length l can pass the delay loop without any collisions owing to frequency shift at the modulator.

When the input lightwave is modulated by a base-band signal such as a nonreturn-to-zero (NRZ) signal, f_m should be larger than the bandwidth of the signal (f_s), in order to reduce crosstalk between different order channels. Thus, f_r should be slightly smaller than $f_s \times p_{\max}$, where $p_{\max}$ is the greatest number of circulation steps. The output optical frequency is shifted to be $f_0 + pf_m$, when the SSB modulator generates the upper side-band. However, we can compensate the shift by using an additional delay line, whee the lower side-band is used.

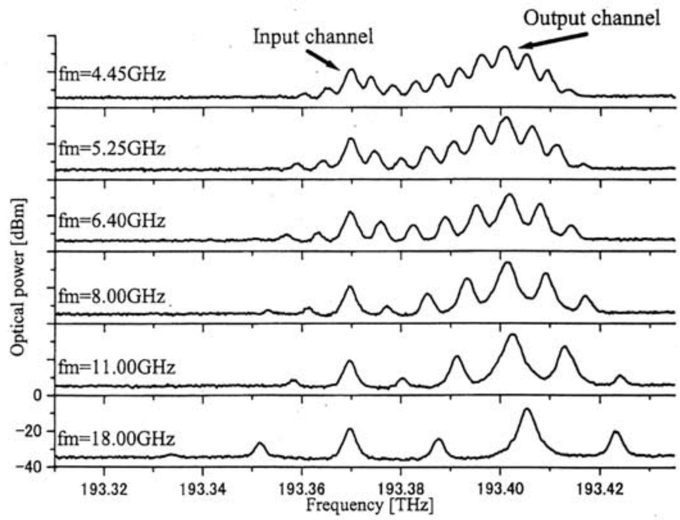

Fig. 3. Optical sectra of the output.

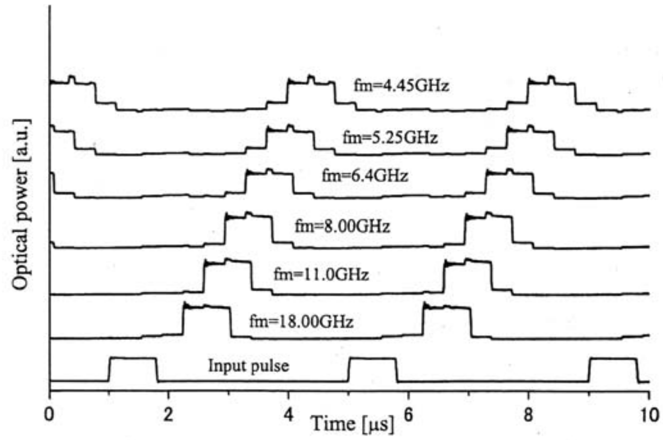

Fig. 4. Time-domain envelopes of the output.

III. Results

Figs. 3 and 4 show the frequency-domain spectra and the time-domain envelopes of the output lightwaves. The input lightwave was intensity modulated by a train of pulses whose period and duty ratio were, respectively, 4 μs and 20% as shown in the plot at the bottom of Fig. 4. An FBG was placed at the optical output port to eliminate the spectrum component of the input lightwave reflected at the FBG located between the two circulators. The reflection band width f_r was 22.5 GHz full-width at half-maximum (FWHM), and the edge slope width Δf_r was 6.0 GHz. Δf_r was defined by the width of the slope where the reflectivity is from 10% to 90% of the maximum. We used an x-cut lithium niobate optical SSB modulator, as the optical frequency shifter. The modulator has a pair of balanced Mach-Zehnder interferometers [6], where

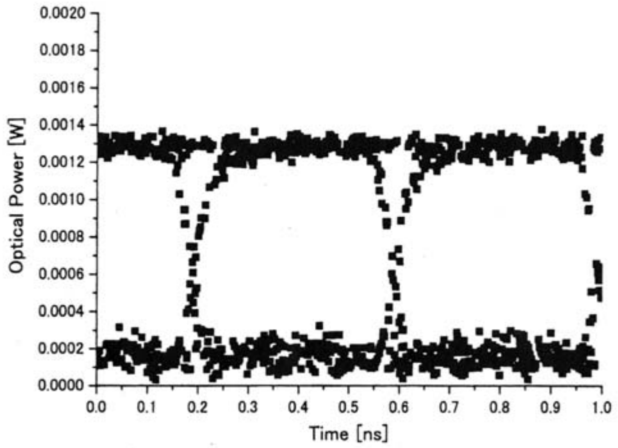

Fig. 5. Eye diagram of an input ligtwave.

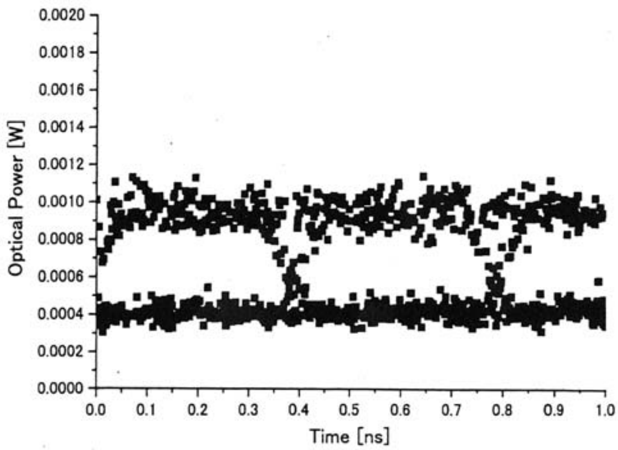

Fig. 6. Eye diagram of an output lightwave, where f_m = 18.0 GHz (second channel).

the carrier-suppression ratio was over 25 dB, and the frequency conversion loss was 23 dB. The dc-bias voltages were adjusted to maximize the first order upper side-band in the output of the SSB modulator. An optical amplifier was used, as shown in Fig. 1, to compensate for loss at the modulator. The gain and noise figure of the amplifier were, respectively, 9.60 dB and 5.32 dB, when the input optical frequency and power were 193.4 THz and −25 dBm.

When f_m = 18.00 GHz, the second-order channel is the primary channel in the output Similarly, when f_m = 11.00, 8.00, 6.40, 5.25, and 4.45 GHz, the primary channels were the third, fourth, fifth, sixth, and seventh channels, respectively. In the case of f_m = 18.00 GHz, the peak of the primary channel exists at 193.406 THz, where the optical frequency of the input lightwave is 193.370 THz. As shown in Fig. 4, the delay can be controlled by changing the frequency of the electric signal fed to the SSB modulator. The delay due to one step of the circulation (τ) corresponding to the time difference between adjoining channels, was 350 ns, while the pulsewidth is 800 ns. In the cases of f_m = 5.25 and 4.45 GHz, undesired spectral components in the outputs were not negligible, as shown in Fig. 3, because f_m is not larger than Δf_r. The time-domain profiles shown in the figure are deformed due to overlapping of the adjacent channels onto the primary one. As shown in Figs. 5 and 6, we also measured the eye diagram of an input lightwave and that of an output lightwave, where the input was intensity modulated by a 2.5-Gb/s NRZ signal, and f_m was 18.00 GHz. The zero level of the output was larger than that of the input. The fluctuation of the mark level was also larger in the output. Q-factors of the second, third, fourth, and fifth channels were, respectively, 3.40, 2.83, 2.04, and 1.62, while that of the input lightwave was 4.87. We deduced that the deformation of the signal was caused by the interference between different order channels at the optical amplifier or was due to undesired channel present in the output.

IV. Conclusion

The authors described an electrically tunable delay line that is composed of an optical SSB modulator, an FBG, and an optical fiber loop. The number of times a lightwave circulates in the loop can be controlled by the electric signal fed to the modulator. Packets of any lengths can go through our proposed delay line without any collisions, even if the length of the packet is larger than that of the delay loop. We demonstrated that the delay at the 100p can be changed by switching the frequency of the electric signal fed to the modulator.

Acknowledgment

The authors would like to express their appreciation to M. Yamada and H. Harai for helpful discussions.

References

[1] S. Yao, B. Mukherjee, and S. Dixit, "Advances in photonic packet switching: An overview," *IEEE Commun. Mag.*, pp. 84−94, Feb. 2000.

[2] D. K. Hunter and I. Andonovic, "Approaches to optical internet packet switching," *IEEE Commun. Mag.*, pp. 116−122, Sept. 2000.

[3] S. Shimotsu, S. Oikawa, T, Saitou, N. Mitsugi, K. Kubodera, T. Kawanishi, and M. Izutsu, "LiNbO3 optical single-sideband modulator," in *OFC 2000*, vol. Paper PD-16.

[4] ——,"Single side-band modulation performance of a LiNbO3 integrated modulator consisting of four-phase modulator waveguides," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 364−366, Mar. 2001.

[5] S. Shimotsu, M. Izutsu, T. Kawanishi, S. Oikawa, and M. Sasaki. "Wideband frequency conversion with LiNbO3 optical single-sideband modulator," in *OFC 2001*, Paper WK3-1 .

[6] K. Higuma, S. Oikawa, Y. Hashimoto, H.Nagata, and M. Izutsu, "X-cut lithium niobate optical single-sideband modulator," *Electron. Lett.*, vol. 37, pp. 515−516, 2001.