A Novel Sliding-Frequency Guiding Filter for Soliton Transmission

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***Abstract*— The Gordon–Haus effect can be substantially reduced by using the sliding-frequency guiding filters. However, a long-distance (such as transoceanic) soliton transmission system may require hundreds of these filters operating at slightly different wavelengths from each other. Thus, it would be difficult in practice to produce and install such a large number of these filters all operating at different wavelengths. In this letter, we demonstrate a novel sliding-frequency guiding filter which automatically offsets its peak wavelength from the wavelength of soliton pulses. Thus, these filters can guide the soliton pulses to slightly different wavelengths continuously, although they are made to be identical.**

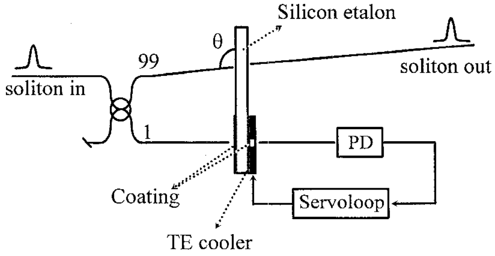

Fig. 1. A schematic diagram of the proposed sliding-frequency guiding filter. PD and TE coolers are a photodetector and a thermoelectric cooler, respectively.

I. INTRODUCTION

SOLITON transmission technique has been improved rapidly since the advent of erbium-doped fiber amplifiers (EDFA's). It has been demonstrated that optically amplified soliton pulses using EDFA's are well suited for the transmission of high-speed signal over ultralong distances [1]. However, the random walk of soliton pulses caused by the amplified spontaneous emission (ASE) of optical amplifiers, known as the Gordon–Haus effect, could impose a significant limitation on the maximum transmission distance and bitrate per channel [2]. There are basically two approaches to reduce this limitation: soliton control in time domain and in frequency domain. The first technique requires retiming of soliton pulses using synchronous modulation, thus resembling conventional regenerators [3]–[4]. Although it is possible to achieve practically unlimited transmission distance using this technique, it not only requires high-speed active devices but is difficult for use in WDM systems. The second technique uses simple bandpass filters distributed along the transmission line [5]. This technique does not require any active component and can be easily applied to a WDM system. However, the ASE noise accumulated within the filter's passband could still limit the performance of an ultralong distance transmission system. Recently, a sliding-frequency guiding filter has been proposed to overcome this problem [6]–[7]. This technique could suppress the ASE accumulation by gradually translating the peak wavelength of the bandpass filters distributed along the transmission line. These filters could be realized easily by using simple etalons with low finesse. However, a long-distance (such as transoceanic) soliton tranmission system may require hundreds of these filters operating at slightly different wavelengths from each other. Thus, it would be difficult in practice to produce and install such a large number of these filters all operating at different wavelengths. In this paper, we demonstrate a novel fiber coupled sliding-frequency guiding filter which automatically offsets its peak wavelength from the soliton wavelength.

II. EXPERIMENT

Fig. 1 shows a schematic diagram of the sliding-frequency guiding filter. The filter was made by using a polished silicon wafer. The 0.5-mm-thick silicon wafer was divided into two parts: one half was coated on both sides with multilayer SiO_2/TiO_2 coatings, while the other half was left uncoated. The free spectral range of this etalon was measured to be 0.67 nm. The finesse of the coated side was about 7. The finesse of the uncoated side should be about 3 nm since the refractive index of silicon is 3.48 at 1.55μm. However, it was measured to be 2.0. This is because of the imperfect optical surfaces and parallelism of the silicon wafer used in this work. The insertion of loss of the uncoated etalon was about 0.5 dB.

The silicon etalon was packaged in an aluminum housing with two commercial beam expanders. These beam expanders were used to direct the soliton pulses to the coated and uncoated sides of the silicon wafer separately. A 20-dB coupler was used to tap one percent of soliton pulses and sent to the coated side. Thus, soliton pulses were mostly directed to the uncoated side. The beam expander used for the coated side was mounted normal to the silicon wafer. A thermoelectric (TE) cooler was attached to the coated side of the silicon wafer. Thus, the coated etalon could be frequency-locked to the incoming soliton wavelength by changing the temperature,

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Manuscript received April 24, 1996; revised May 22, 1996. This work was supported by the Korea Ministry of Information & Communication and Opto-Electronics Research Center at the Korean Advanced Institute of Science and Technology.

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Publisher Item Identifier S 1041-1135(96)06574-3.

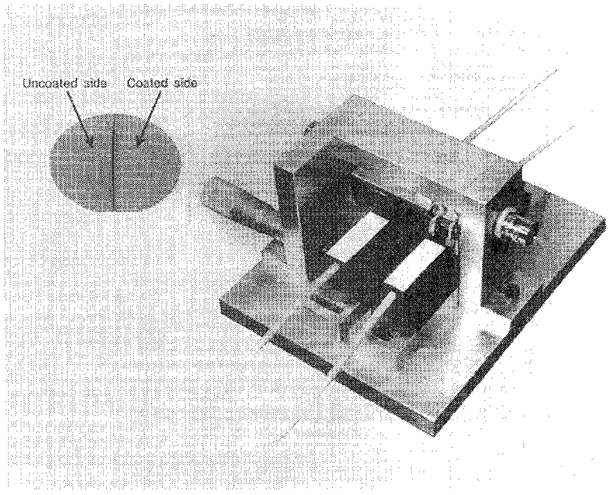

Fig. 2. A photograph of the proposed sliding-frequency guiding filter. The incident angle to the uncoated side was adjusted by using a micrometer.

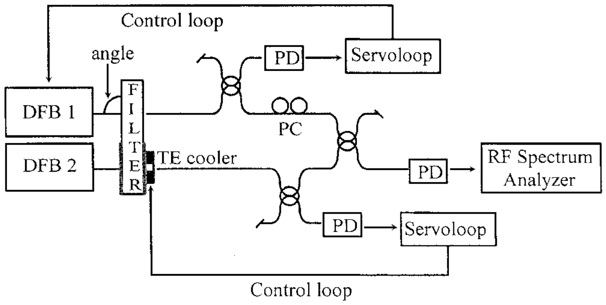

Fig. 3. Experimental setup to determine the sliding rate.

which, in turn, changed the refractive index of the silicon wafer [8]. For the frequency-locking, the temperature of the coated etalon was slightly dithered at about 1 Hz by modulating the current of the TE cooler. The uncoated side was used as a guiding filter since it formed a low-strength etalon (finesse ≈ 2.0), which was adequate as a guiding filter. The difference between the peak wavelengths of coated and uncoated sides of the silicon etalon determines the sliding rate. This difference could be adjusted to a desired value by changing the incident angle of θ to the uncoated side, since the incident angle to the coated side was fixed. A micrometer was attached to control the incident angle of the beam expander used for the uncoated side of the silicon wafer. Fig. 2 shows a photograph of the proposed sliding-frequency guiding filter.

Fig. 3 shows the experimental setup to determine the sliding rate. A DFB laser (DFB1) operating at about 1.55 μm was locked to the corresponding resonant frequency of the uncoated side. The resonant frequency of the coated side was locked to the frequency of another DFB laser (DFB2) by using the TE cooler attached to the filter. The sliding rate is the same as the difference between the resonant frequencies of the coated and uncoated sides of the etalon. Thus, the incident angle to the uncoated side of the etalon can be adjusted for the desired sliding rate by monitoring the beat frequency between the DFB lasers.

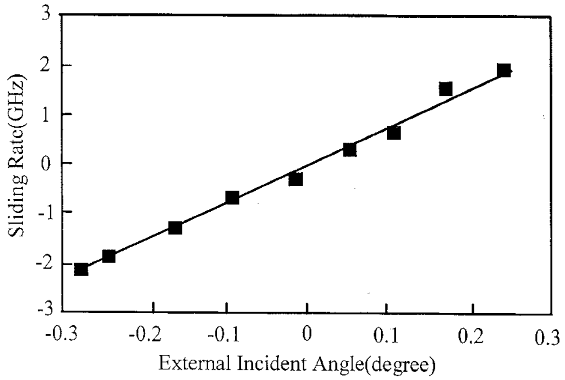

Fig. 4. The measured sliding rate versus external incident angle in comparison with a theoretically calculated line (solid line). The result shows that the resonant frequency of the silicon etalon was tuned about 7.83 GHz/°C.

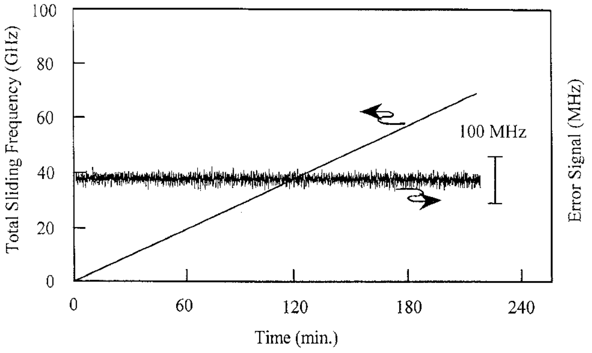

Fig. 5. Measured trackability of the proposed filter. The resonant frequency of the coated side was locked to the wavelength of the incoming solitons. Then, the error signal was measured while tuning the wavelength of the incoming solitons gradually. The vertical axis on the left represents the amount of translated soliton frequency.

III. RESULTS

Fig. 4 shows the measured sliding rate as a function of the incident angle. The result shows that the resonant frequency was shifted about 7.83 GHz/°C, which was in good agreement with the calculated value of 8.27 GHz/°C. It would require about 300 amplifiers and sliding-frequency guiding filters to transmit soliton pulses over the transoceanic distances of about 10 Mm [9]. Although the sliding rate may differ in various systems, it is usually in the range of 100–500 MHz/filter. Thus, we set the incident angle to the uncoated silicon to be about 0.02 °C for 150-MHz sliding. When these filters are used at every 33 km for the soliton transmission over 10 Mm, the total sliding frequency would be about 45 GHz. It can be achieved easily by changing the temperature of the filter only about 4 °C, since the silicon filter can be tuned about 11 GHz/°C.

The proposed sliding-frequency guiding filter should be able to track the wavelength of soliton pulses changing gradually along the transmission line. Fig. 5 shows the measured trackability of the proposed filter. The error signal from the coated etalon frequency-locked to the incoming laser wavelength was measured while gradually changing the laser wavelength as in the soliton transmission line. In this experiment, a CW laser was used instead of a soliton source. The same technique could be applied to a pulsed source (such as soliton) without deleterious degradation of frequency stability [10]–[11]. The 3-dB passband of the coated etalon was about 12 GHz. This would be wide enough to accommodate the broadened spectral width of soliton pulses. The result shows that the peak wavelength of the proposed filter could track the soliton wavelength within 50 MHz. Thus, we confirmed that this filter operated properly even when the total sliding frequency was greater than 70 GHz.

IV. SUMMARY

The Gordon–Haus effect can be substantially reduced by using the sliding-frequency guiding filters. However, a transoceanic soliton transmission system may require hundreds of these filters operating at slightly different wavelengths from each other. Thus, it would be impractical to produce and install such a large number of these filters all operating at different wavelengths. To avoid this problem, we demonstrated a novel sliding-frequency guiding filter. This filter was made by coating one half of a silicon wafer with multilayer dielectric coatings, while leaving the other half uncoated. The coated side of the silicon wafer was used to lock the filter's peak wavelength to the incoming soliton wavlength by using temperature. The uncoated side was used to guide soliton pulses. The peak wavelength of the uncoated side was set to be slightly different from the wavelength of the coated side by adjusting its incident angle. As a result, this filter automatically offsets its peak wavelength from the wavelength of incoming soliton pulses. Thus, these identical filters, made of the same design, could be used throughout the soliton transmission line instead of the numerous filters all operating at different wavelengths.

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