Spectrum analysis technique for measuring time delay of light in SOI micro-ring slow light device

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Abstract: Spectrum analysis technique is introduced to measure the time delay of the silicon-on-insulator (SOI) micro-ring slow light device. The interference spectra of the TE and the TM polarization are obtained based on dual-quadrature spectral interferometry technique. By analyzing the observed spectral interference, the phase and time delay of the output optical pulse of SOI micro-ring is estimated. This method has a very high accuracy of time measurement because it avoids the impact of response speed of optoelectronic device, and moreover, it provides a complete measurement of the complex electric field as a continuous function of frequency.

Keywords: SOI micro-ring, time delay, spectrum analysis

1. Introduction

Optical buffer can store the packet, which can solve the problem of node collision when transmitting packets in optical domain, and will become an important element in Optical network. A SOI micro-ring decreases group velocity of light through the coupled resonance and can be used to a buffer, which has becomes a hot research because of its many advantages, such as simple process, flexible control, and easy integration. There have been a lot of reports on the theoretical design and fabrication of the SOI micro-ring[1-4], but few papers have been reported about the time delay measurement and phase extracting. For the traditional measurement method，the time delay can be detected directly by an oscilloscope or a photon counter. However, the time delay of tens of picoseconds or less is difficult to be detected through these electronic equipments because of being limited by their response speed. In order to solve this problem, the spectrum analysis technique is introduced in this paper. By analyzing the observed spectral interference, the phase difference between the unknown and the reference pulse is obtained. The time delay can be obtain from the slope of the phase difference with frequency curve without considering dispersion effect for the small device. Moreover, the spectrum analysis technique can extract the phase of the output optical field as the reference pulse is known in both amplitude and phase. The phase is a very important physical parameter because it determines the width of the free spectrum and quality factor of the SOI micro-ring.

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2. Dual-quadrature spectral interferometry

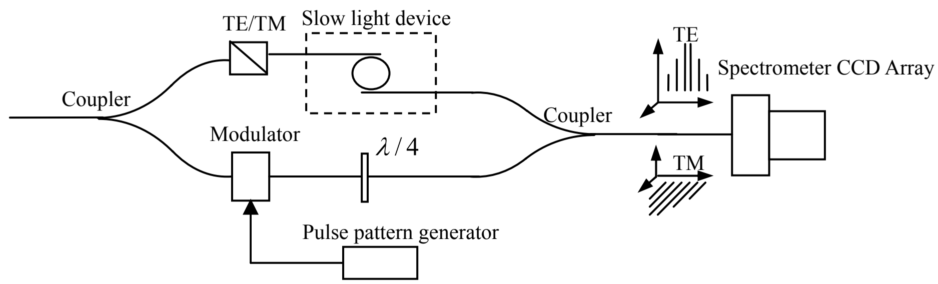

Fig. 1 DQSI experimental setup for a phase sensitive measurement of the output optical pulse of the SOI micro-ring slow light device

As shown in Fig. 1, Dual-quadrature spectral interferometry (DQSI) is based on a frequency resolved Mach-Zehnder interferometer[5-6]. The SOI micro-ring slow light device is placed in one arm of the interferometer, generating the unknown optical pulse, whose polarization state is determined by a TE/TM polarization controller. We write the two polarization states of the pulse as $[E_{TM}(\omega), E_{TE}(\omega)]$. The reference pulse, going through the other arm of the interferometer, is circularly polarized by a quarter-wave plate, so that its two linear polarization components are $[E_0(\omega), E_0(\omega)e^{j\pi/2}]$. Both beams are recombined in an optical fiber coupler, and the interference spectra of TE and TM are successively recorded by a spectrometer CCD array detector. The signals measured for the two polarization components are given by

$$\left|E_{TM}(\omega)+E_0(\omega)\right|^2 = \left|E_{TM}(\omega)\right|^2 + \left|E_0(\omega)\right|^2 + 2\,\mathrm{Re}\,E_0^*(\omega)E_{TM}(\omega)$$

$$\left|E_{TE}(\omega)+E_0(\omega)e^{j\pi/2}\right|^2 = \left|E_{TE}(\omega)\right|^2 + \left|E_0(\omega)\right|^2 + 2\,\mathrm{Im}\,E_0^*(\omega)E_{TE}(\omega) \qquad (1)$$

During data acquisition, shutters on both arms of the interferometer are operated in order to extract the non-interferometric part of the signal. After subtraction of these terms, only the cross terms in Eq. (1) remain. The reference pulse precedes the unknown pulse by a fixed time delay τ generating a phase of $\omega\tau$, and so the cross terms are written by

$$I_{TM}(\omega) = 2\,\mathrm{Re}\,E_{TM}(\omega)E_0^*(\omega)e^{j\omega\tau}$$

$$I_{TE}(\omega) = 2\,\mathrm{Im}\,E_{TE}(\omega)E_0^*(\omega)e^{j\omega\tau} \qquad (2)$$

By solving the above two equations simultaneously, the phase difference between the reference and the unknown pulse can be obtained by

$$\phi_{unk}(\omega) - \phi_{ref}(\omega) + \omega\tau = \arctan\left[\frac{|E_{TM}(\omega)| I_{TE}(\omega)}{|E_{TE}(\omega)| I_{TM}(\omega)}\right] \quad (3)$$

Dispersion effect of SOI micro-ring device is ignored because its length is very small and the transmission energy is low, so the two phase ϕ_{unk} and ϕ_{ref} are independent of frequency. In this case the phase difference is equal to $\omega\tau$ and should vary linearly with respect to frequency, and therefore τ can be obtained from the slope of the phase difference with frequency curve.

3. Analysis of the results

We performed the time delay retrieval procedure described above. The transmission spectra of the SOI micro-ring were picked from Ref. [4]. The measured transmission spectra for the two polarization states are shown in Fig. 2 with blue and red curves, respectively.

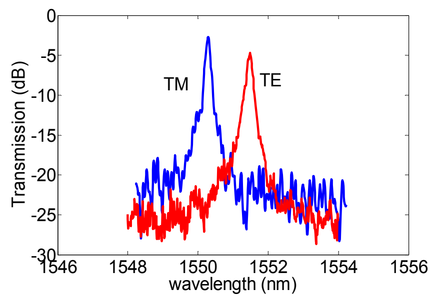

Fig. 2 Transmission spectra of the TE and the TM polarization picked from Ref. [4].

The modulated reference light is Gaussian pulse, its expression in frequency domain as follows:

$$E_0(\omega) = \sqrt{2\pi} e^{-\frac{(\omega-\omega_0)^2}{2F^2}} \quad (4)$$

Where ω_0 is the center frequency; and F is the half-width.

The simulated spectral interferogram between the reference and the unknown beam is shown in Fig. 3.

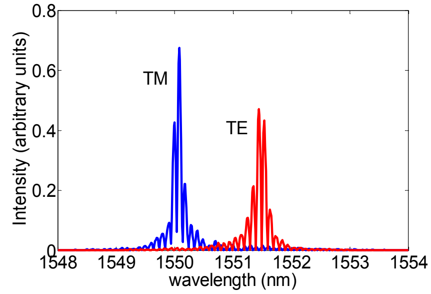

Fig. 3 Spectral interferograms from the both polarization components between the reference beam and the unknown beam

By Fourier transforming the spectral interferograms, we obtain

$$F^{-1}I_a(\omega) = S(t-\tau) + S(-t-\tau) \tag{5}$$

where a represents the TE polarization or the TM polarization. Because the measured signal $I_a(\omega)$ is real, i.e., the sum of $E_a(\omega)E_0^*(\omega)e^{j\omega\tau}$ and its complex conjugate, the inverse Fourier transform is the sum of two terms, time reversed from each other, whose separation in time increase with τ. $S(t)$ is the correlation product between the reference and the unknown electric field. Choosing τ larger than the pulse cycle, we find that the two terms in Eq. (5) do not overlap in time. Therefore we can single out the relevant term $S(t-\tau)$ by multiplying the equation by the Heaviside function $H(t)$. Finally, a Fourier transform allows us to recover $E_a(\omega)E_0^*(\omega)e^{j\omega\tau}$, in both amplitude and phase, and the complex electric field can be obtained by using the following expression:

$$E(\omega) = \frac{F\left[H(t)F^{-1}I_a(\omega)\right]\exp(-j\omega\tau)}{E_0^*(\omega)} \tag{6}$$

The unknown electric field is obtained from Eq. (6) and its amplitude is shown in Fig. 4.

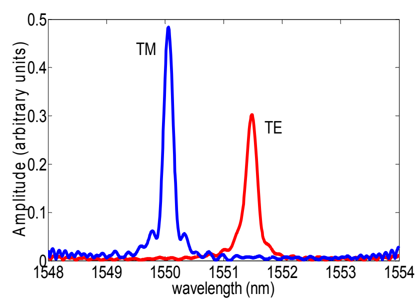

Fig. 4 The amplitude of the unknown electric field

The phase difference between the reference and the unknown pulse extracted by Eq. (3) results in a principal value of phase between $-\pi$ and $+\pi$ regardless of the actual value of the phase difference, as is shown in Fig. 5(a). Phase unwrapping is carried out in order to remove phase difference ambiguities by adding or subtracting a 2π value at individual pixel until the difference between adjacent pixels is less than π. The phase difference varying with frequency continuously is shown in Fig. 5(b). The time delay can be obtain from the slope of the phase difference with frequency curve, and here the value τ is 40 ps.

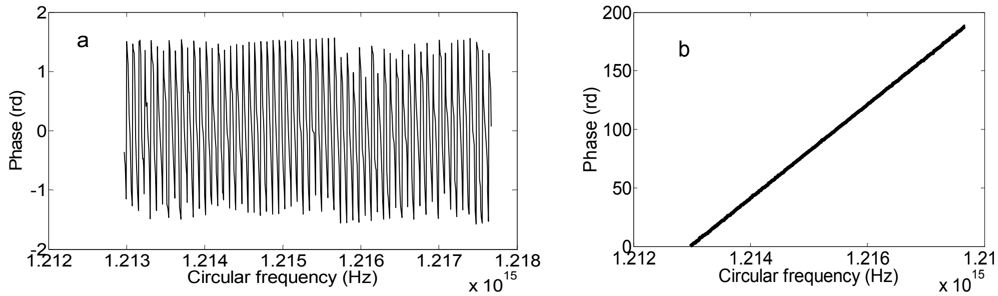

Fig. 5 The phase difference with frequency curve: (a) the phase distribution having discontinuities that are due to the principal-value calculation; (b) continued profile of the phase distribution.

4. Conclusion

In order to measure the ultrashort time delay of the SOI micro-ring accurately, DQSI technique is introduced. By analyzing the observed spectral interference, the phase difference between the reference and the unknown pulse is extracted. The time delay can be obtain from the slope of the phase difference with frequency curve without considering dispersion effect for the small device. This method is simple to implement, very sensitive, and provide a complete measurement of the complex electric field of the SOI micro-ring as the reference pulse is known in both amplitude and phase.

Acknowledgments

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