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Measurement of small chirp-parameter for Mach-Zehnder-type optical modulator

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ABSTRACT

A new measurement method of chirp-parameters is proposed for electro-optic (EO) intensity modulators with the Mach-Zehnder (MZ) waveguide interferometer. This method is suitably applied for the measurement of the small chirp with operation at a specific RF-frequency. To determine the chirp-parameter, optical spectrum components of the modulated light are observed with varying the relative optical phase difference between the two arms of the MZ waveguide interferometer. The chirp-parameter of 0.17, which is a value small enough for EO intensity modulation, was successfully measured by the experiment.

1. Introduction

The light chirp in the optical intensity modulation means a parasitic phase shift as the intensity is varied. Electro-optic (EO) intensity modulators using the Mach-Zehnder (MZ) waveguide structure are known to have a low-chirp performance compared with other types of optical modulation, such as, the direct modulation of semiconductor lasers or the absorption modulation [1].

Since the light chirp causes an optical-frequency variation, wave forms of the light intensity transmitted through an optical fiber are degraded by the chirp combined with the fiber dispersion. The performance in long-haul optical fiber transmissions is usually affected by the chirp. On the other hand, the chirp may induce redundant optical sideband components in the spectrum of the modulated light. Recent applications of EO modulators such as ultra high-bit rate optical communication systems or microwave clock signal generation [2] is sensitively affected by such spectrum disturbance. High-quality modulation with extremely small-chirp, or zero chirp, is therefore required. To support the development of such small-chirp modulators, accurate evaluation of the small chirp-parameters is indispensable.

A simple method for the chirp measurement has been reported by using the fiber dispersion [3]. This indirect measurement method requires light signals modulated by RF frequencies over a considerably wide range. Based on this principle, a practical chirp measurement technique has been proposed using a fiber interferometer for high-speed measurement [4]. Another indirect method proposed before is for characterizing an optical pulse and a temporal modulator by the analysis of the two-dimensional spectrogram of the pulse gated by the modulator [5]. By using this method, the light chirp induced by the modulator can be determined from the optical phase variation obtained by the characterization of the optical pulse. The other type of the chirp measurement is a direct method with observing the optical spectrum and is applicable for the single RF-frequency modulation. Some reports have been presented on the direct measurement [6–9]. However evaluation of small chirp-parameters is comparably difficult for this method because changes in the optical spectrum with the chirp are considerably slight. The direct method was preferably applied for the case of relatively large chirp.

In this letter, we present a new direct-measurement method of the light chirp available for MZ modulators. This proposed method is suitably applied for the case of the small chirp by observing

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optical spectrum components of the modulated light with varying the relative optical phase difference between the two arms of the MZ waveguide interferometer.

2. Measurement of chirp parameter

In the MZ modulators, light intensity modulation is realized by interference between two phase-modulated lightwaves. When A_1 and A_2 represent amplitudes of the optical phase modulation in two arms of the MZ interferometer, the electric field of light output from the interferometer is expressed by

$$Ee^{j\phi}e^{j\omega_0 t} = \frac{E_{\mathrm{in}}}{2}\left[e^{-j\{A_1\cos(\omega_{\mathrm{m}}t+\phi_{\mathrm{m}})+\phi_{\mathrm{B1}}\}} + e^{-j\{A_2\cos(\omega_{\mathrm{m}}t+\phi_{\mathrm{m}})+\phi_{\mathrm{B2}}\}}\right]e^{j\omega_0 t}, \quad (1)$$

where E, ϕ and ω_0 are amplitude of the electric field, phase retardation induced by the modulation and angular frequency of lightwaves, respectively. E_{in}, ω_{m} and ϕ_{m} are amplitude of the electric field of the input light, angular frequency of the RF signal and initial phase shift of the RF signal, respectively. ϕ_{B1} and ϕ_{B2} are optical phase shifts in the two arms, which are determined by the optical path length of each arm. We assume an equal split of the input light power between two arms of the MZ interferometer. The attenuation of lightwaves is ignored in the discussions. ϕ means a parasitic phase shift in the intensity modulated light and is related to the light chirp.

A_1 and A_2 normally have opposite signs with each other. Assuming $A_1 > 0$ and $A_2 < 0$, the light modulation index is given by

$$A = A_1 - A_2. \quad (2)$$

An amount of chirp is expressed by the chirp-parameter, α, which is defined by [1]

$$\alpha = \frac{d\phi}{dt}\bigg/\left(\frac{1}{E}\frac{dE}{dt}\right). \quad (3)$$

MZ modulators are preferably operated at $\Delta\phi_{\mathrm{B}} = \phi_{\mathrm{B1}} - \phi_{\mathrm{B2}} = \pi/2$, which is the most sensitive state for the intensity modulation. $\Delta\phi_{\mathrm{B}}$ represents phase bias in the interference due to the optical path difference in the MZ interferometer. At the condition of the small modulation and $\Delta\phi_{\mathrm{B}} = \pi/2$, α is approximately expressed as

$$\alpha \approx \frac{A_1 + A_2}{A_1 - A_2}. \quad (4)$$

This equation presents an amount of unbalance in phase modulation between two arms. It is seen that in the case of the completely balanced operation, $A_1 = -A_2$, no chirp is included in the light output. From (2) and (4), A_1 and A_2 are given by

$$\begin{cases} A_1 = (\alpha+1)A/2 \\ A_2 = (\alpha-1)A/2 \end{cases}. \quad (5)$$

The frequency spectrum of the modulated light is given by expansion of (1) with Bessel functions as

$$Ee^{j\phi}e^{j\omega_0 t} = \frac{E_{\mathrm{in}}}{2}\sum_{n=-\infty}^{\infty}\left\{J_n(A_1)e^{-j(\phi_{\mathrm{B1}}+n\phi_{\mathrm{m}})} + J_n(A_2)e^{-j(\phi_{\mathrm{B2}}+n\phi_{\mathrm{m}})}\right\}e^{j(\omega_0+n\omega_{\mathrm{m}})t}, \quad (6)$$

where J_n is a Bessel function of the first kind. Intensity of the nth order sideband component is expressed by using α, A and $\Delta\phi_{\mathrm{B}}$ as

$$\frac{I_n}{I_{\mathrm{in}}} = |J_n\{(\alpha+1)A/2\} + J_n\{(\alpha-1)A/2\}e^{j\Delta\phi_{\mathrm{B}}}|^2, \quad (7)$$

where I_{in} is the input light intensity. In (7), $n = 0$ corresponds to the carrier component. Fig. 1 shows I_0, I_1 and I_2 as functions of $\Delta\phi_{\mathrm{B}}$ in cases of $\alpha = 0$ and 0.5. Intensity of the odd order sideband components is minimized at $\Delta\phi_{\mathrm{B}} = 0$ and that of the even order ones including the carrier is done at $\Delta\phi_{\mathrm{B}} = \pi$. When the light chirp exists,

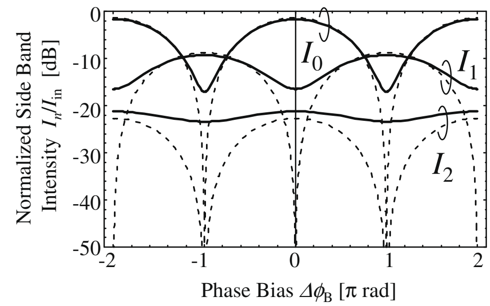

Fig. 1. Intensity of sideband components, I_0, I_1 and I_2, normalized by the input light intensity as functions of the phase bias, $\Delta\phi_{\mathrm{B}}$, when $A = 0.5\pi$ rad. Dotted lines and solid lines correspond to $\alpha = 0$ and 0.5, respectively.

sideband components are not completely suppressed at each minimum transmission point and the residual intensity of the components is very sensitive to α. Here we consider the suppression ratio SR_n of the nth order sideband component which is a maximum-to-minimum intensity ratio, $I_{n\max}/I_{n\min}$, as

$$SR_n = \frac{I_{n\max}}{I_{n\min}} = \left[\frac{|J_n\{(\alpha+1)A/2\}| + |J_n\{(\alpha-1)A/2\}|}{|J_n\{(\alpha+1)A/2\}| - |J_n\{(\alpha-1)A/2\}|}\right]^2, \quad (8)$$

where $|\alpha| < 1$ is assumed. The SR_n can be measured as an intensity extension ratio of each sideband component with varying $\Delta\phi_{\mathrm{B}}$ from 0 to π. By using this relationship the chirp-parameter α is calculated from SR_n. Fig. 2 shows SR_1 and SR_2 as functions of α with parameters of A.

Here we use SR_2, the suppression ratio of the second sideband components, for determining the chirp-parameters accurately even in cases of small modulation indices. The optical spectrum can generally be observed with a dynamic range more than 50 dB even by an optical spectrum analyzer commercially available. The SR_2 of more than 15 dB corresponds to α less than 0.1 from Fig. 2b. α less than 0.1 should be easily determined by measuring SR_2 with a normal spectrum analyzer as long as the wavelength resolution is high enough to distinguish neighboring

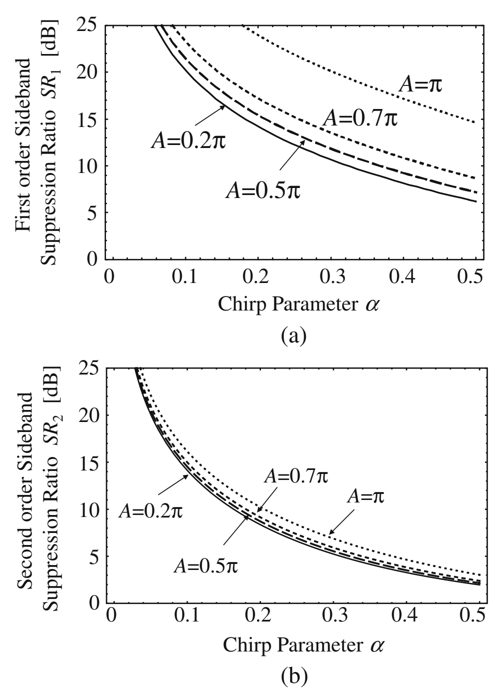

Fig. 2. Intensity suppression ratios of the first order sideband component (a) and the second order sideband component (b) as functions of chirp-parameter α.