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Impact of dispersion order on optical millimetre-wave generation based on series optical external modulators without an optical filter

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The influence of higher order fiber dispersions (like chromatic dispersion and dispersion slope) on the optical millimeter-wave generation is studied. Optical sideband suppression ratio and radio frequency spurious suppression ratio are given and discussed. Moreover, the mathematical results of the proposed model are verified by experiments and numerical simulations.

Keywords: fiber chromatic dispersion, microwave photonics, radio-over-fiber, dual-drive Mach–Zehnder modulator.

1. Introduction

Nowadays, microwave photonics (MWP) is a key technology in radio-over-fiber (RoF) systems due to large bandwidth, secure data transmission and no electromagnetic interference (EMI), *etc.* [1–3]. Various applications of MWP include, among others, a radar, communication system, sensor network, warfare systems [4–12]. A dual-drive Mach–Zehnder modulator (DD-MZM) plays an important role due to large bandwidth and better performance as compared to the direct modulation [5]. However, a signal suffers more seriously because of chromatic dispersion and dispersion slope of a fiber and it results in the degradation of the transmission range of the transmission system.

Over the last few decades, various methods have been proposed to generate the optical mm-wave generation using single-MZM [13], dual-MZM [12, 14, 15], triple-MZM [16] and quad-MZM configurations [12]. In 2010, XIANGLING LIU *et al.* proposed a model to overcome chromatic dispersion using one dual-parallel MZM [17]. Similarly, YANG CHEN *et al.* proposed a method to reduce fiber chromatic dispersion using a MZM with three arms [18].

Various research groups proposed different models of cascaded and parallel optical modulators for frequency multiplication in RoF systems. For example, the frequency quadrupling mm-wave with frequency terms less than 15 dB is obtained using 2-cascaded MZMs [19]. The 2-series modulators are used for frequency sextupling with 20 dB OSSR (optical sideband suppression ratio) [20]. An optical octupling mm-wave with 13dB OSSR also results when using 2-cascaded MZMs [14]. Some researchers also presented parallel MZMs configuration [16]. The advantage of using parallel configuration is that sextupling, 12-tupling and 18-tupling can be achieved [21].

Recently, the author has studied the impact of both individual and combined higher order fiber dispersion on MWP links [13, 15, 22]. In this paper, the author extended the investigation to a series of MZMs configurations without an optical filter.

The paper is organised as follows: Section 2 includes analytical expression derivation of fiber dispersion for the proposed model, followed by the mathematical analysis of fiber dispersion on the optical mm-wave generation based on two DD- MZMs without an optical filter. In Section 3, Q-factor, BER and eye diagram are investigated. Finally, Section 4 presents conclusions.

2. Proposed model and analysis

The schematic diagram for the optical mm-wave generation based on two DD-MZMs without an optical filter is shown in Fig. 1. A continuous light wave from a laser is used as an optical carrier (expressed as $E_0\cos(\omega_0 t)$, where E_0 is the amplitude of the optical field, and ω_0 is the angular frequency of the optical carrier). An optical carrier of 193.1 THz and an electrical drive signal of frequency 12.5 GHz are applied to both MZM1 and MZM2.

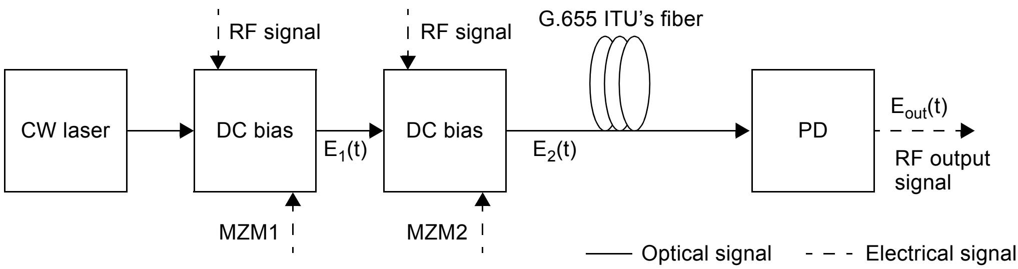

Fig. 1. Schematic diagram of the optical mm-wave signal generation based on two DD-MZMs. CW – continuous wave, MZM – Mach–Zehnder modulator, G.655 – International Telecommunication Union's standardized fiber, PD – photodiode.

The electric field equation at the output of the MZM1 up to n terms can be written as follows [14, 22–24]:

$$E(t) = E_0 \cos(\Phi/2) A_1(t) + E_0 \sin(\Phi/2) A_2(t) \tag{1}$$

where

$$A_1(t) = \cos\left(\omega_0 t + \frac{\Phi}{2}\right) J_0(\beta) + \sum_{n=1}^{\infty} (-1)^n J_{2n}(\beta) \left\{ \cos\left[\omega_0 t + 2n(\omega_{\mathrm{RF}} t + \phi) + \frac{\Phi}{2}\right] + \right.$$
$$\left. + \cos\left[\omega_0 t - 2n(\omega_{\mathrm{RF}} t + \phi) + \frac{\Phi}{2}\right] \right\}$$

$$A_2(t) = \sum_{n=1}^{\infty} (-1)^n J_{2n-1}(\beta) \left\{ \cos\left[\omega_0 t + (2n-1)(\omega_{\mathrm{RF}} t + \phi) + \frac{\Phi}{2}\right] + \right.$$
$$\left. + \cos\left[\omega_0 t - (2n-1)(\omega_{\mathrm{RF}} t + \phi) + \frac{\Phi}{2}\right] \right\}$$

and $\beta = \pi V_{\mathrm{RF}}/2V_{\pi}$ is a modulation depth, V_{RF} is the amplitude of the applied low frequency RF signal, Φ is the phase difference between the arms of the modulator, ϕ is the phase of the electrical drive signal, ω_{RF} is the angular frequency of RF signal and ω_0 is the angular frequency of an optical carrier. Both modulators are biased at the maximum transmission point (MAX-TP). The electric field at the output of MZM1 can be written as:

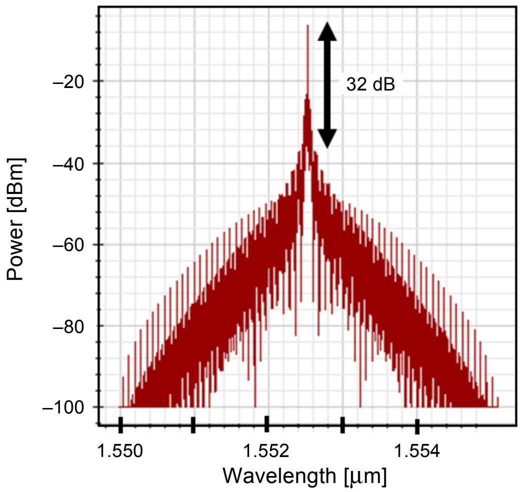

Fig. 2. Simulation optical spectra of the generated optical mm-wave with DD-MZM1 based at the maximum transmission point.

$$E_1(t) = E_0\Big[J_0(\beta_1)\cos(\omega_0 t) - J_2(\beta_1)\cos(\omega_0 t - 2\omega_{\mathrm{RF}} t - 2\phi_1) + \\ - J_2(\beta_1)\cos(\omega_0 t + 2\omega_{\mathrm{RF}} t + 2\phi_1)\Big] \tag{2}$$

OSSR comes out to be 32 dB (see Fig. 2). Spectrum has start, center and stop points at 1.55253, 1.5497 and 1.55536 μm, respectively. The maximum range is found to be –1.52 dBm and the minimum range comes out to be nearly –104.69 dBm. The electric field at the output of MZM2 is given by

$$\begin{aligned} E_2(t) = E_0\Big[& J_2(\beta_1)J_2(\beta_2)\cos(\omega_0 t - 4\omega_{\mathrm{RF}} t - 2\phi_1 - 2\phi_2) + \\ & - J_2(\beta_1)J_0(\beta_2)\cos(\omega_0 t - 2\omega_{\mathrm{RF}} t - 2\phi_1) + \\ & - J_0(\beta_1)J_2(\beta_2)\cos(\omega_0 t - 2\omega_{\mathrm{RF}} t - 2\phi_2) + \\ & + J_2(\beta_1)J_2(\beta_2)\cos(\omega_0 t - 2\phi_1 + 2\phi_2) + \\ & + J_0(\beta_1)J_0(\beta_2)\cos(\omega_0 t) + \\ & + J_2(\beta_1)J_2(\beta_2)\cos(\omega_0 t + 2\phi_1 + 2\phi_2) + \\ & - J_0(\beta_1)J_2(\beta_2)\cos(\omega_0 t + 2\omega_{\mathrm{RF}} t + 2\phi_2) + \\ & - J_2(\beta_1)J_0(\beta_2)\cos(\omega_0 t + 2\omega_{\mathrm{RF}} t + 2\phi_1) + \\ & + J_2(\beta_1)J_2(\beta_2)\cos(\omega_0 t + 4\omega_{\mathrm{RF}} t + 2\phi_1 + 2\phi_2)\Big] \end{aligned} \tag{3}$$

where ϕ_1 and ϕ_2 are the initial phases of the applied RF electrical drive signal of MZM1 and MZM2, respectively, and β_1 and β_2 are the modulation depth of the MZM1 and MZM2, respectively.

From Figure 3, OSSR comes out to be 32 dB. Spectrum has start, center and stop points at 1.55253, 1.5479 and 1.55536 μm, respectively. Numerical simulation gives the maximum and minimum range nearly –1.90 and –104.6 dBm, respectively. A small value of the minimum range is generally due to noise generation in the modulation process. Considering initial phases of the applied RF electrical drive signal for both MZMs equal to zero, the optical signal at the end of the transmission over an ITU G.655 can be obtained by adding the transmission phase delay $(\beta(\omega_0 \pm 2n\omega_{\mathrm{RF}})L)$ to the corresponding optical sideband shown in Eq. (3). By expanding the propagation constant $\beta(\omega)$ of the G.655 fiber for each optical sideband using Taylor series around the angular frequency of the optical carrier [25], we get

$$\beta(\omega_0 \pm 2n\omega_{\mathrm{RF}}) = \beta(\omega_0) + \frac{\mathrm{d}\beta}{\mathrm{d}\omega}(\pm 2n\omega_{\mathrm{RF}}) + \frac{1}{2}\frac{\mathrm{d}^2\beta}{\mathrm{d}\omega^2}(\pm 2n\omega_{\mathrm{RF}})^2 + \\ + \frac{1}{6}\frac{\mathrm{d}^3\beta}{\mathrm{d}\omega^3}(\pm 2n\omega_{\mathrm{RF}})^3 + \ldots \tag{4}$$

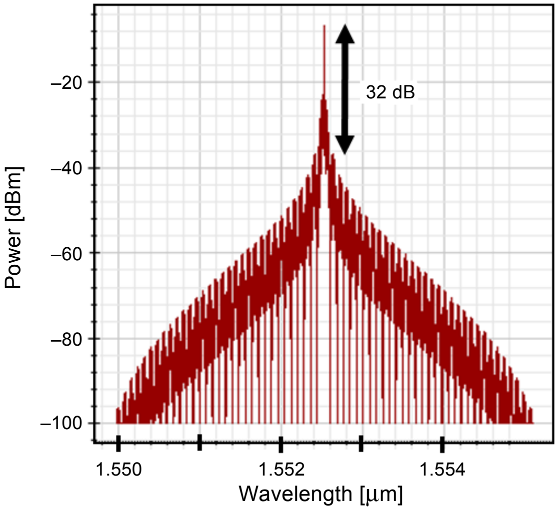

Fig. 3. Simulation optical spectra of the generated optical mm-wave with DD-MZM2 based at the maximum transmission point.

Let $\beta^1(\omega_0) = \dfrac{\mathrm{d}\beta}{\mathrm{d}\omega}$, $\beta^2(\omega_0) = \dfrac{\mathrm{d}^2\beta}{\mathrm{d}\omega^2}$, and $\beta^3(\omega_0) = \dfrac{\mathrm{d}^3\beta}{\mathrm{d}\omega^3}$. The second-order dispersion parameter is given by [25]

$$\beta^2(\omega_0) = \frac{\mathrm{d}\tau}{\mathrm{d}\omega} = \frac{\lambda^2}{2\pi c}\frac{\partial\tau}{\partial\lambda} = \frac{\lambda^2}{2\pi c}D \tag{5}$$

where D is the group velocity dispersion (GVD). The third-order dispersion parameter or dispersion slope is given by [25]

$$\begin{aligned}\beta^3(\omega_0) &= \frac{\mathrm{d}^2\tau}{\mathrm{d}\omega^2} = \frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2\frac{\partial^2\tau}{\partial\lambda^2} + 2\lambda\frac{\partial\tau}{\partial\lambda}\right] = \\ &= \frac{\lambda^2}{(2\pi c)^2}[\lambda^2 D_1 + 2\lambda D]\end{aligned} \tag{6}$$

where D_1 is the dispersion slope.

Radio frequency spurious suppression ratio (RFSSR) comes out to be 28 dB (see Fig. 4). Spectrum has start, center and stop points at 1.59961×10^{11}, -1.59961×10^{10} and 3.35918×10^{11} m, respectively. From the OptiSystem software simulation, the maximum range and minimum range are 4.30 and –104.9 dBm, respectively. Inserting dispersion parameters in Eq. (3) up to the third order with the help of Eqs. (4), (5) and (6), the electric field at the output of MZM2 with dispersion is given by

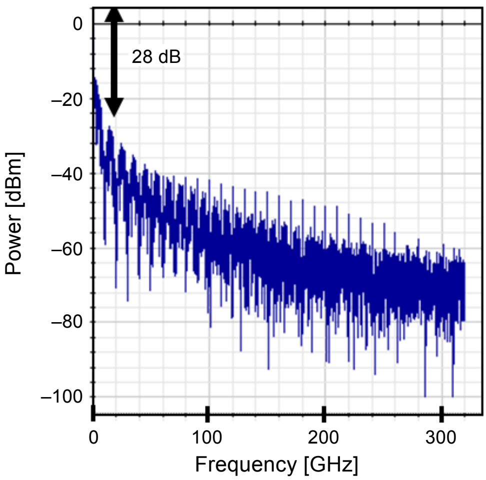

Fig. 4. RF spectrum of the simulated mm-wave signal generation with 12.5 GHz RF driven signal.

$$\begin{aligned} E_2(t) = E_0\Big\{ & \left[J_0(\beta_1)J_0(\beta_2) + 2J_2(\beta_1)J_2(\beta_2)\right]\cos(\omega_0 t + \beta(\omega_0)L) + \\ & - 2\left[J_2(\beta_1)J_0(\beta_2) + J_0(\beta_1)J_2(\beta_2)\right]A_1(t)\,A_2(t) + \\ & + 2J_2(\beta_1)J_2(\beta_2)\,A_3(t)\,A_4(t)\Big\} \end{aligned} \tag{7}$$

where:

$$A_1(t) = \cos\left[\omega_0 t + \beta(\omega_0)L + \frac{1}{2}\beta^2(\omega_0)(2\omega_{\mathrm{RF}})^2 L\right]$$

$$A_2(t) = \cos\left[2\omega_{\mathrm{RF}}\,t + \beta^1(\omega_0)(2\omega_{\mathrm{RF}}L) + \frac{1}{6}\beta^3(\omega_0)(2\omega_{\mathrm{RF}})^3 L\right]$$

$$A_3(t) = \cos\left[\omega_0 t + \beta(\omega_0)L + \frac{1}{2}\beta^2(\omega_0)(4\omega_{\mathrm{RF}})^2 L\right]$$

$$A_4(t) = \cos\left[4\omega_{\mathrm{RF}}\,t + \beta^1(\omega_0)(4\omega_{\mathrm{RF}}L) + \frac{1}{6}\beta^3(\omega_0)(4\omega_{\mathrm{RF}})^3 L\right]$$

The output intensity of a photodetector is given by $I_{\mathrm{PD}}(t) = \Re\left|E_2\,E_2^*\right|$.

3. Experiment and results

The experimental setup to study the dispersion order is similar to Fig. 1. A continuous-wave light from a tunable laser (Yokogawa AQ2200-136) with a power of 20 dBm at

1550 nm is used. Both MZMs are biased at the maximum transmission point (MAX-TP). Also, the extinction ratio for both modulators is more than 30 dB. A 12.5 GHz local oscillator signal from a microwave signal generator (Anritsu-MG3694) is applied to the MZMs. The signal is detected by PD (U2T MPDV1120RA) with a 3 dB cutoff frequency of 35 GHz and a responsivity of 0.6 A/W. Then, the electrical signal is analyzed by an electrical spectrum analyzer (ESA). In this section, the impact of fiber dispersion on the optical mm-wave generation is studied and verified with help of both Matlab software and OptiSystem simulator. ITU's G.655 fiber parameters are used for Matlab software and OptiSystem simulations [26].

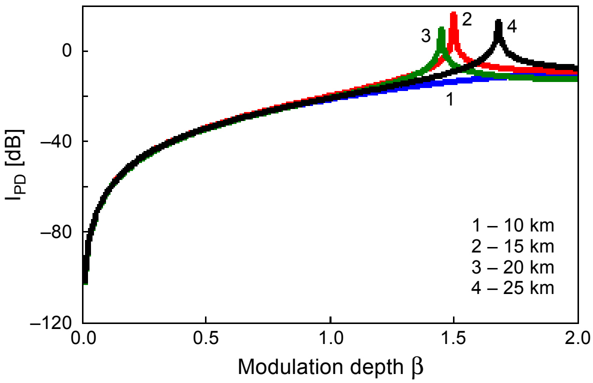

Fig. 5. Plot of intensity I_{PD} at the output of a photodetector *vs.* modulation depth β for both DD-MZMs biased at MAX-TP under the combined effect of $\beta^2 + \beta^3$.

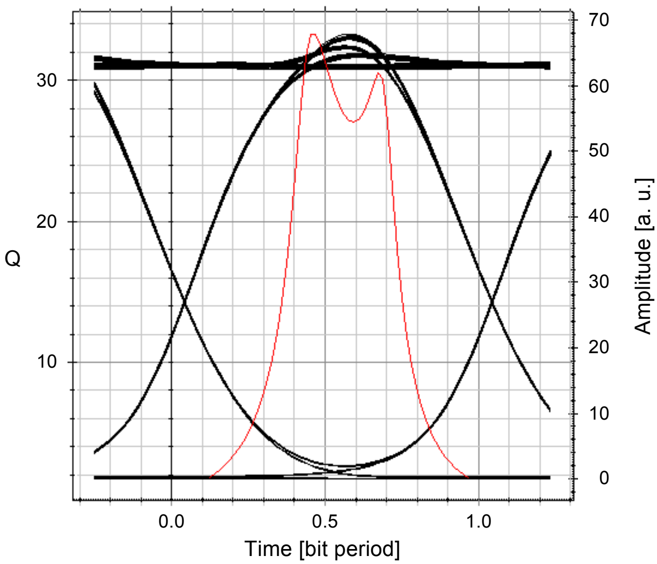

Fig. 6. Simulated eye diagram of the baseband signal using ITU's G.655 fiber of 10 km under the combined effect of $\beta^2 + \beta^3$.

Figure 5 shows that better performance occurs for the fiber of length L equal to 25 km and worst performance is shown by the fiber of length L equal to 20 km. When the transmission distance is 10 km, the Q-factor is approximately 33.2601, min BER is 7.29022×10^{-24} and eye height is approximately equal to 0.057437 (see Fig. 6).

Here, better performance occurs for the fiber of length L equal to 25 km and worst performance is shown by the fiber of length L equal to 10 km (as in Fig. 7). When the

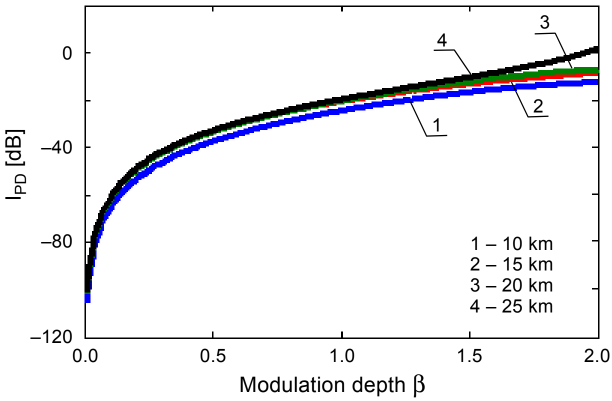

Fig. 7. Plot of intensity I_{PD} at the output of a photodetector *vs.* modulation depth β for both DD-MZMs biased at MAX-TP under the effect of β^2 only.

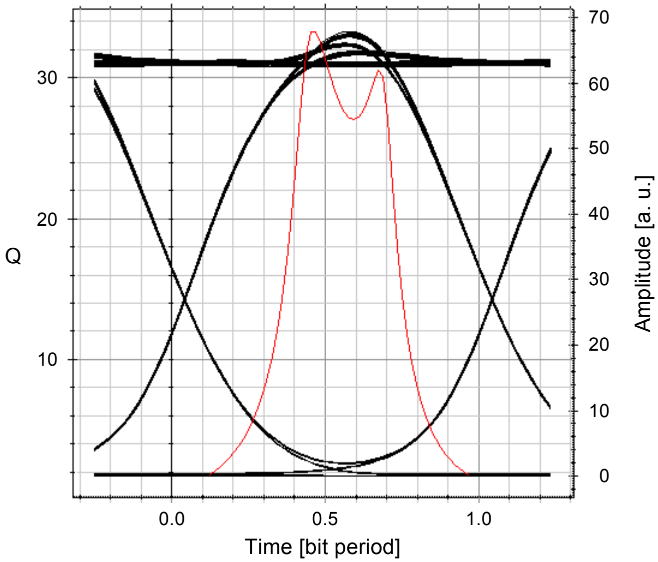

Fig. 8. Simulated eye diagram of the baseband signal using ITU's G.655 fiber of 10 km under the effect of β^2.

transmission distance is 10 km, the Q-factor is approximately 32.2477, min BER is 1.11259×10^{-24}, eye height is approximately equal to 0.05743 (see Fig. 8).

For this case, better performance occurs for the fiber of length L equal to 25 km and worst performance is shown by the fiber of length L equal to 10 km (Fig. 9). When the transmission distance is 10 km, the Q-factor is approximately 308.303, min BER is nearly equal to 0, eye height is nearly equal to 0.06228 (see Fig. 10). It has been

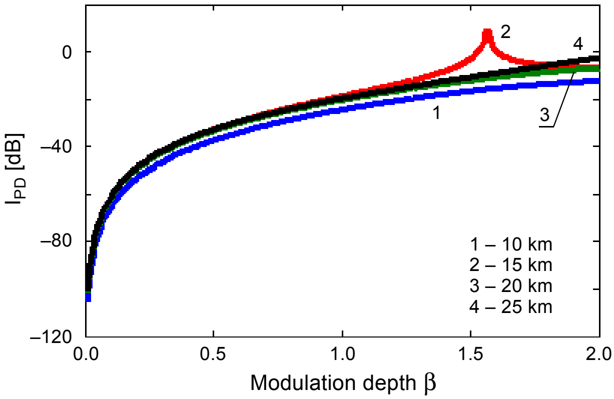

Fig. 9. Plot of intensity I_{PD} at the output of a photodetector *vs.* modulation depth β for both DD-MZMs biased at MAX-TP under the effect of β^3 dispersion parameter only.

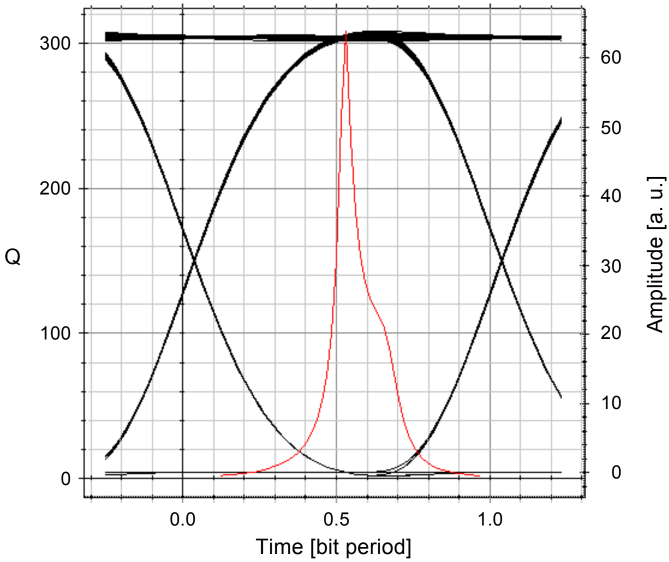

Fig. 10. Simulated eye diagram of the baseband signal using ITU's G.655 fiber of 10 km under the combined effect of β^3.

T a b l e 1. Comparison of output intensity of photodetector I_{PD} with different modulation index β for MAX-TP (MZM1) and MAX-TP (MZM2).

	Dispersion parameters	Length of fiber [km]	I_{PD} [dB]	
			with $\beta = 1$	with $\beta = 2$
Simulation readings	$\beta^2 + \beta^3$	10	–21.12	–13
		15	–20.22	–9.3
		20	–21.12	–13
		25	–20.22	–7.901
	β^2 only	10	–22.6	–5.02
		15	–20.72	–8.00
		20	–20.72	–8.05
		25	–20.72	–7.176
	β^3 only	10	–24.61	–12.61
		15	–18.92	–7.08
		20	–18.62	–7.181
		25	–18.70	–2.748
Experimental readings	$\beta^2 + \beta^3$	10	–20.18	–12.12
		15	–19.23	–8.2
		20	–20.11	–12.5
		25	–19.24	–6.02
	β^2 only	10	–21.53	–4.23
		15	–19.11	–7.02
		20	–19.14	–7.26
		25	–19.26	–6.23
	β^3 only	10	–23.12	–11.66
		15	–17.15	–6.00
		20	–17.23	–6.24
		25	–17.21	–1.99

found that the output intensity of a photodetector is reduced by the combined effect of $\beta^2 + \beta^3$ (consider Table 1 for simulation and experimental readings). The dominating dispersion parameter is dispersion curvature β^3.

4. Conclusion

This paper presents both experimental and simulation results for the influence of chromatic dispersion and dispersion slope of a fiber on the optical mm-wave signal generation without an optical filter. We show that the chromatic dispersion has no effect on the intensity and frequency response even at large modulating frequency and large propagation distance. It has been observed that the dispersion slope has a significant impact on the optical mm-wave generation and results in fading of the optical millimeter signal.

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