

Microwave harmonic generation in fiber-optical links

Attila Hilt

Abstract — Optical transmission of microwave (MW) and millimeter-wave (MMW) signals has become an intensive research area in the last decade. There is a growing interest in optical processing of MW signals [1, 2], phased array applications [3] and wireless distribution of broadband data in fiber-fed MMW subscriber access systems [4 – 10]. This paper extends the existing models of MW/MMW optical links that are based on optical intensity [10, 11]. The model is suitable for estimating harmonic levels of the MW modulation signal generated in the optical path. Considering a MW fiber-optic link both the optical transmitter and the receiver are responsible for harmonic generation. Furthermore, the optical fiber itself inserted between the transmitter and receiver induces harmonics due to dispersion. Exact modelling of harmonic generation requires a calculation based on the optical field instead of on a purely intensity basis [12 – 14].

Keywords — optical transmission, fiber dispersion, microwaves, harmonics, IM/DD, coherent model, fiber length-bandwidth product.

1. High-speed modulation of light

In interferometric modulators the light of the optical source is splitted into two beams and then interference is created between these beams (Fig. 1). Interferometric optical modulators are usually called Mach-Zehnder modulators (MZM).

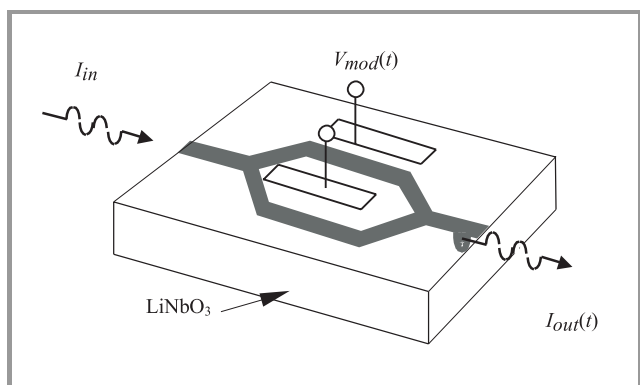


Fig. 1. MZM integrated on LiNbO₃ (one arm modulated).

A phase modulator is inserted into one branch inducing phase difference between the beams. If the phase difference is π a rejection of the input optical signal occurs. When the beams interfere constructively, the output intensity is equal to the input intensity assuming lossless modulator ($A = 1$).

If the power dividers split and recombine the optical power equally, the output intensity is written as:

$$I_{out}(t) = A \frac{I_{in}}{2} (1 + \cos \varphi(t)) = AI_{in} \cos^2 \frac{\varphi(t)}{2}, \quad (1)$$

where A is the optical loss in the modulator and $\varphi(t)$ is the phase difference between the propagating waves,

$$\varphi(t) = \pi \frac{V_{mod}(t)}{V_{\pi}} = \pi \frac{V_{DC} + V_{RF}(t)}{V_{\pi}}. \quad (2)$$

Figure 2 shows the modulator transmittance as a function of the modulation voltage. V_{DC} is the bias voltage of the modulator. The half-wave voltage V_{π} introduces π phase difference between the modulator arms. This voltage is required to drive the modulator between adjacent minima and maxima. Applying periodic modulation as:

$$V_{mod}(t) = V_{DC} + V_{RF} \cos(\omega_{RF}t) \quad (3)$$

the intensity becomes

$$I_{out}(t) = \frac{I_{in}}{2} [1 + \cos(\pi\gamma + \pi\alpha \cos \omega_{RF}t)], \quad (4)$$

where $\gamma = V_{DC}/V_{\pi}$ and $\alpha = V_{RF}/V_{\pi}$ are the normalized bias and RF signal amplitudes driving the MZM, respectively. The optimal DC bias for linear operation is: $V_{DC} = V_{\pi}/2 + iV_{\pi}$ where $i \in Z$. The case of $i = 0$ is called the quadrature.

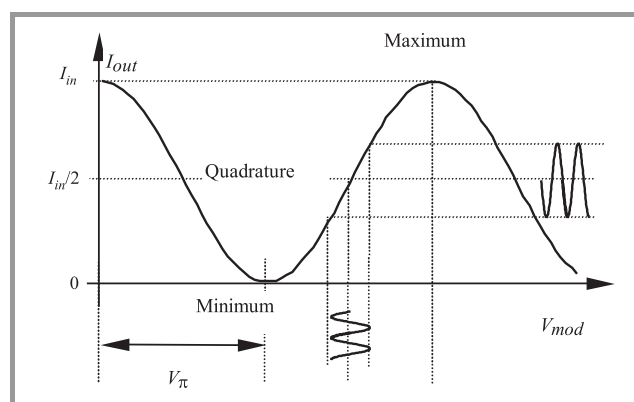


Fig. 2. Calculated double sided optical intensity spectrum at linear operation ($\gamma = 0.5$ or 1.5) for $\alpha = 0.25$.

The output optical intensity can be expressed from Eq. (4) by Bessel-function expansion:

$$I_{out}(t) = \frac{I_{in}}{2} + \frac{I_{in}}{2} \cos(\gamma\pi) \times \left\{ J_0(\alpha\pi) + 2 \sum_{k=1}^{+\infty} (-1)^k J_{2k}(\alpha\pi) \cos[2k\omega_{RF}t] \right\} + \left\{ -\frac{I_{in}}{2} \sin(\gamma\pi) \times \left[2 \sum_{k=1}^{+\infty} (-1)^k J_{2k+1}(\alpha\pi) \cos[(2k+1)\omega_{RF}t] \right] \right\}. \quad (5)$$

Equation 5 indicates that due to nonlinearity of the modulation function the output intensity contains harmonics of the modulation frequency ω_{RF} in spite of that the modulation voltage is an ideal sinusoid. The double sided intensity spectrum has been calculated at the MZM output by fast Fourier transform (FFT) as a function of the harmonic number k . From the general expression of Eq. (5) the special cases are the quadrature (or linear) operation, the minimum and the maximum transmission modes. If the MZM is biased for linear operation the intensity contains only odd harmonics and a DC component (Fig. 3).

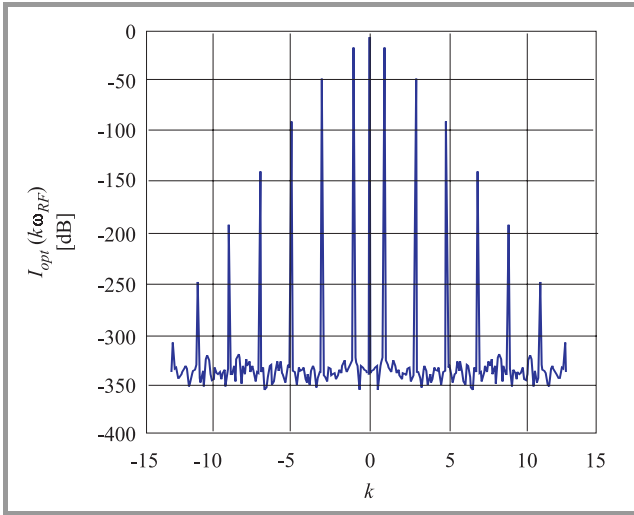


Fig. 3. Calculated double sided optical intensity spectrum at maximum transmission ($\gamma = 2$), for $\alpha = 0.25$.

In Fig. 4 the MZM is biased for maximum transmission. Compared to Fig. 3, odd harmonics disappeared and only even harmonics of the modulation signal are present in the intensity spectrum. The DC term has larger amplitude but the modulation signal and all its odd harmonics are strongly suppressed. In other words, at this special bias point the MZM generates second harmonic of the modulation signal (Fig. 4). Such special operation modes find interesting applications in transmission of MMW signals over dispersive fiber as well as in optical generation of MMW signals. Considering small modulation indices

(of $V_{RF}(t) \ll V_\pi$ so $\alpha \ll 1$) and a DC bias for linear operation with $\gamma = 1.5$, Eqs. (4) and (5) simplify to:

$$I_{out}(t) = \frac{I_{in}}{2} \left[1 + \cos\left(\frac{3}{2}\pi + \pi\alpha \cos \omega_{RF}t\right) \right] = \frac{I_{in}}{2} \left[1 + \sin(\pi\alpha \cos \omega_{RF}t) \right] \approx \frac{I_{in}}{2} [1 + m \cos \omega_{RF}t], \quad (6)$$

where $m = \alpha\pi$ denotes the optical modulation depth (OMD). Small-signal modulation allows linear approximation of the sinusoidal modulator transmittance function. Let us suppose now that the MZM is biased at quadrature for linear operation. Power level of the detected fundamental signal and any odd harmonic can be calculated as a function of MZM driving voltage:

$$P_{DET}(n, V_{RF}) = \frac{R_{50}}{8} (R_{PD} J_{out})^2 = \frac{R_{50}}{8} R_{PD}^2 I_{in}^2 A^2 J_n^2\left(\pi \frac{V_{RF}}{V_\pi}\right), \quad (7)$$

where $n = 2k + 1$; R_{50} stands for the resistive load and $n = 1$ means the detected fundamental signal. Optical intensities at the modulator input and output are denoted by I_{in} and I_{out} , respectively. In Eq. (7) a resistive matching to the 50 Ω load is supposed. Figures 5 and 6 show harmonic levels as a function of MW power and DC bias driving the modulator, respectively.

The optical field at the MZM output is:

$$E(t) = E_0 \cos \omega_0 t \cos \left[\gamma \frac{\pi}{2} + \alpha \frac{\pi}{2} \cos \omega_{RF}t \right]. \quad (8)$$

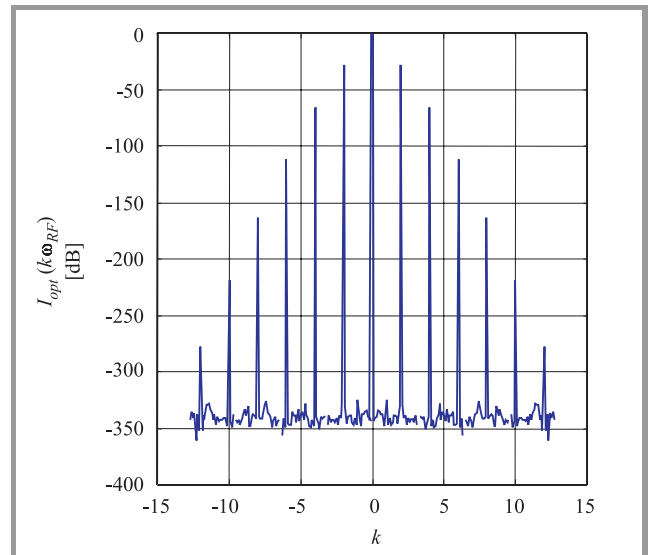


Fig. 4. Fundamental and odd harmonics of the detected optical intensity versus MW driving power; $I_{in} = 1.2$ mW, $A = 3$ dB, $V_\pi = 5$ V, $R_{PD} = 0.8$ A/W.

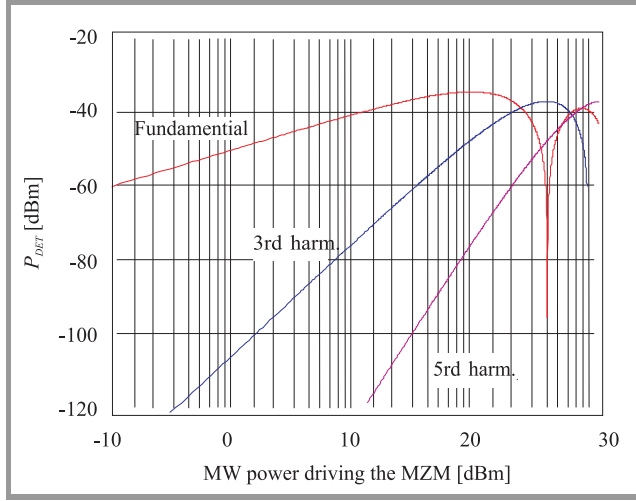


Fig. 5. Detected DC and harmonic contents versus γ (calculated with $I_{opt} = 400 \mu\text{W}$, $R_{PD} = 0.356 \text{ A/W}$, $m = 0.586$).

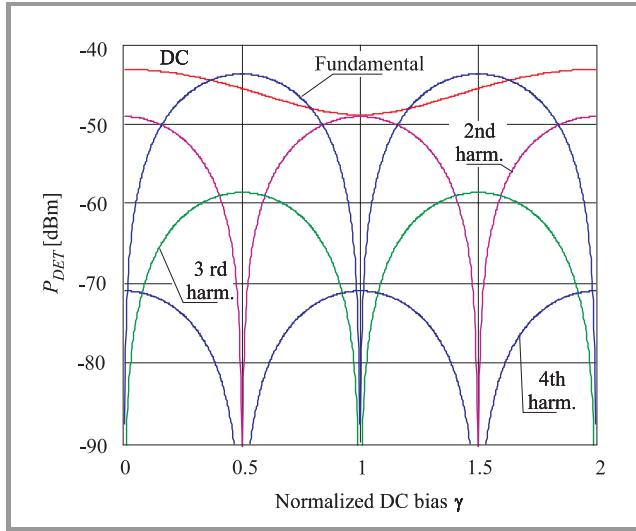


Fig. 6. Maximum SMF length L resulting 3 dB C/N degradation versus dispersion parameter D .

In Eq. (8) $E_0 \cos \omega_0 t$ is the optical carrier. The optical field expressed from Eq. (8) by Bessel-function expansion is:

$$\begin{aligned}
 E(t) = & E_0 J_0\left(\alpha \frac{\pi}{2}\right) \cos\left(\gamma \frac{\pi}{2}\right) \cos \omega_0 t + \\
 & -E_0 J_1\left(\alpha \frac{\pi}{2}\right) \sin\left(\gamma \frac{\pi}{2}\right) \cos\left(\omega_0 \pm \omega_{RF}\right) t + \\
 & -E_0 J_2\left(\alpha \frac{\pi}{2}\right) \cos\left(\gamma \frac{\pi}{2}\right) \cos\left(\omega_0 \pm 2\omega_{RF}\right) t + \\
 & +E_0 J_3\left(\alpha \frac{\pi}{2}\right) \sin\left(\gamma \frac{\pi}{2}\right) \cos\left(\omega_0 \pm 3\omega_{RF}\right) t + \dots \quad (9)
 \end{aligned}$$

2. Quadratic photodetection

Usually the photocurrent calculated by Eq. (10) and said to be proportional to the modulated optical intensity [15]:

$$i_{PD}(t) = R_{PD} P_{opt}(t). \quad (10)$$

In Eq. (10) the phase information of the optical wave is lost. Since in a coherent model the phase cannot be neglected, let us consider now the general case when instead of the intensity the optical field is given:

$$i_{PD}(t) \propto R_{PD} 2 \langle E^2(t) \rangle = R_{PD} \langle E(t) E^*(t) \rangle. \quad (11)$$

Here, $\langle \rangle$ means time averaging taken over a few optical periods, $E(t)$ represents a real valued function and factor 2 is chosen for later convenience [16]. Time averaging means the physical fact, that the PD cannot response to rapid changes at optical frequencies, only the MW/MMW modulation envelope of the optical carrier is detected. Supposing an incident optical field as a combination of two spectral components having the same polarization:

$$\begin{aligned}
 i_{PD}(t) & \propto R_{PD} 2 \left\langle \left[E_1 \cos(\omega_1 t + \phi_1) + \right. \right. \\
 & \quad \left. \left. + E_2 \cos(\omega_2 t + \phi_2) \right]^2 \right\rangle = \\
 & = R_{PD} \left\langle E_1^2 + E_2^2 + E_1^2 \cos 2(\omega_1 t + \phi_1) + \right. \\
 & \quad \left. + E_2^2 \cos 2(\omega_2 t + \phi_2) + \right. \\
 & \quad \left. + 2E_1 E_2 \cos [(\omega_1 - \omega_2)t + \phi_1 - \phi_2] + \right. \\
 & \quad \left. + 2E_1 E_2 \cos [(\omega_1 + \omega_2)t + \phi_1 + \phi_2] \right\rangle = \quad (12) \\
 & = R_{PD} \left\{ E_1^2 + E_2^2 + 2E_1 E_2 \cos [(\omega_1 - \omega_2)t + \phi_1 - \phi_2] \right\}.
 \end{aligned}$$

The above calculation is referred to a coherent beating of the input optical signals. Terms $2\omega_1$, $2\omega_2$ and $\omega_1 + \omega_2$ disappeared due to averaging. Remaining terms represent a DC component and a current having a MW frequency equal to the difference of the input optical frequencies. As seen from Eq. (12) coherent beating can be used to generate MW and MMW signals optically. Let us consider now the optical field present at a MZM output in the case of small OMD. This optical field is approximated now by three spectral lines only. Using the complex form of Eq. (11) we can calculate the photocurrent as:

$$\begin{aligned}
 i_{PD}(t) & \propto R_{PD} 2 \left\langle \left\{ E_{RF} \cos [(\omega_0 - \omega_{RF})t - \phi_1] + \right. \right. \\
 & \quad \left. \left. + E_0 \cos(\omega_0 t) + E_{RF} \cos [(\omega_0 + \omega_{RF})t + \phi_2] \right\}^2 \right\rangle = \\
 & = R_{PD} \left\{ E_{RF} e^{j[(\omega_0 - \omega_{RF})t - \phi_1]} + E_0 e^{j\omega_0 t} + \right. \\
 & \quad \left. + E_{RF} e^{j[(\omega_0 + \omega_{RF})t + \phi_2]} \right\} * \left\{ E_{RF} e^{-j[(\omega_0 - \omega_{RF})t - \phi_1]} + \right. \\
 & \quad \left. + E_0 e^{-j\omega_0 t} + E_{RF} e^{-j[(\omega_0 + \omega_{RF})t + \phi_2]} \right\} = R_{PD} \left[E_0^2 + 2E_{RF}^2 + \right. \\
 & \quad \left. + 4E_0 E_{RF} \cos\left(\frac{\phi_2 - \phi_1}{2}\right) \cos\left(\omega_{RF} t + \frac{\phi_1 + \phi_2}{2}\right) + \right. \\
 & \quad \left. + 2E_{RF}^2 \cos 2\left(\omega_{RF} t + \frac{\phi_1 + \phi_2}{2}\right) \right]. \quad (13)
 \end{aligned}$$

It is seen from Eq. (13) that second harmonic of the modulation signal ω_{RF} is generated, however small OMD and ideal photodetector have been supposed. The modulation signal cannot be recovered if the phase difference $\varphi_2 - \varphi_1$ is equal to $(2n + 1)\pi$. Generally the optical field $E(t)$ is composed of several spectral lines (see Eq. (9)). In this case the exact calculation is difficult, since ω_{RF} components arise from the mutual beating of each pair of spectral lines that are separated by ω_{RF} . Similarly, the harmonic $n\omega_{RF}$ is generated from the beating of any two lines being separated n times ω_{RF} apart. Finally, the photocurrent has a discrete spectrum of:

$$i_{PD}(\omega) \propto R_{PD}(\omega) \sum_{k=0}^{N-1} i(k\omega_{RF}), \quad (14)$$

where N is the number of the optical field spectral components taken into account. The DC term is given by $k = 0$ and $k = N - 1$ gives the higher order harmonic. Calculation by Eqs. (13)–(14) is rather tedious. An easier solution starts with the optical field $E(t)$ given in time domain and uses the complex form of Eq. (11). Then the spectrum of the photocurrent at the PD output can be simply determined by Fourier transform. For calculation simplicity, this method using FFT has been used in our computer simulations:

$$i_{PD}(\omega) \propto R_{PD}(\omega) \mathbf{F} \left\{ E(t) E^*(t) \right\}. \quad (15)$$

3. Effect of chromatic dispersion on MW transmission

Considering small modulation index ($\alpha \ll 1$) and optimal modulator bias for linear operation, the optical field at the MZM output can be approximated by three main spectral components at ω_0 and $\omega_0 \pm \omega_{RF}$ (Eqs. (8)–(9)). This field suffers from dispersion during propagation in a standard single mode fiber (SMF) exhibiting a chromatic dispersion factor of $D = 17$ ps/km/nm. The optical field at the SMF output is calculated with the fiber transfer function $H(\omega)$ approximated by its Taylor series up to the second order:

$$\begin{aligned} E_{out}(\omega) &= E_{in}(\omega) H(\omega) \approx \\ &\approx E_{in}(\omega) e^{-j \left(\beta_0 + \beta_0' \Delta\omega + \beta_0'' \frac{\Delta\omega^2}{2} \right) L}. \end{aligned} \quad (16)$$

For simplicity we omitted the linear fiber attenuation. In the exponent of Eq. (16) the first term results in a phase delay, meanwhile the second term represents the group delay. These terms are out of interest here. However, the third term introduces additional phase change due to chromatic dispersion. Inserting the dispersion parameter D into Eq. (16) from $\beta_0'' = -\lambda^2 D / 2\pi c$, supposing an input optical field of Eq. (9) and applying Eq. (16), the photocurrent after quadratic photodetection is written as:

$$\begin{aligned} i_{PD}(t) &= R_{PD} \left\{ E_0^2 + 2E_{RF}^2 + 4E_0 E_{RF} \cos \left(\frac{LD}{4\pi c} \lambda^2 \omega_{RF}^2 \right) \cdot \right. \\ &\quad \left. \cdot \cos [\omega_{RF}(t - \tau)] + 2E_{RF}^2 \cos [2\omega_{RF}(t - \tau)] \right\}, \end{aligned} \quad (17)$$

where $\tau = \beta_0' L$ is the group delay. As seen in Eq. (17) the detected signal is composed of a DC photocurrent, the fundamental signal delayed by τ and its second harmonic. Neglecting DC and harmonic terms, omitting the delay and inserting $E_{RF} = mE_0/4$ into Eq. (17) the photocurrent at the fundamental of the modulation frequency f_{RF} is:

$$\begin{aligned} i_{PD, \omega_{RF}}(t) &= \\ &= R_{PD} m E_0^2 \cos \left(c D \pi L (f_{RF} / f_{opt})^2 \right) \cos (\omega_{RF} t). \end{aligned} \quad (18)$$

Based on Eq. (18) the electrical power delivered from the matched photodiode to the load is proportional to:

$$\begin{aligned} P_{RF}^{[dB]}(f_{RF}, L, D) &\propto \\ &\propto 10 \log \left\{ (R_{PD} m E_0^2)^2 \cos^2 [c D \pi L (f_{RF} / f_{opt})^2] \right\} \propto \\ &\propto 20 \log \left| \cos [c D \pi L (f_{RF} / f_{opt})^2] \right|. \end{aligned} \quad (19)$$

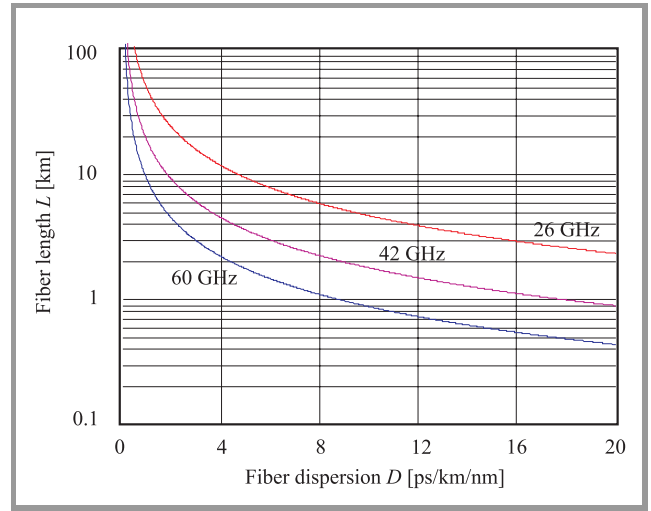


Fig. 7. Measured rejection at $f_{RF} = 14.2$ GHz for a fiber length of $L = 19.2$ km.

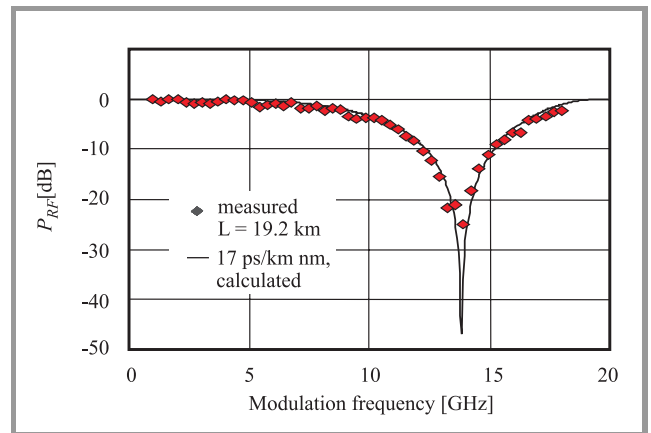


Fig. 8. Measured rejection at $f_{RF} = 14.2$ GHz for a fiber length of $L = 19.2$ km.

As it is shown in Figs. 7 and 8, the phase difference between the spectral components propagating in the fiber can result in a complete rejection of the transmitted MW or MMW signals. In Fig. 8 results obtained by scalar measurements on the $L = 19.2$ km long FDDI ring of our University are compared to the theoretical curve [10].

4. Harmonics in dispersive transmission

In Section 3 the optical field $E(\omega)$ present at the SMF input has been approximated by three spectral lines only. This simplification reduced the calculation difficulties significantly and we were able to derive analytical results. In the general case however, several optical field spectral lines are present at the fiber input. Detected amplitude and phase of these optical field spectral components are determined

by the LD, by the MZM as well as by parameters of propagation in the dispersive fiber. Only coherent models can explain properly detected levels of different harmonics of the modulation signal. Based on the coherent model of the MW optical link we simulated the effect of chromatic dispersion in the general case of several spectral lines. In this coherent model the calculation is based on the optical field and not on the optical intensity. Here we present simulation results for harmonic generation. Harmonics are generated due to propagation in dispersive fiber. When the MZM is biased for linear operation, only odd components are present in the optical intensity (Fig. 3). In the optical field both even and odd spectral components are present (Fig. 9). When this optical field is launched into a SMF, due to dispersion even intensity components will appear after propagation. Calculated levels of harmonics are shown in Fig. 10. Since phase of harmonics are rotated faster in the fiber than

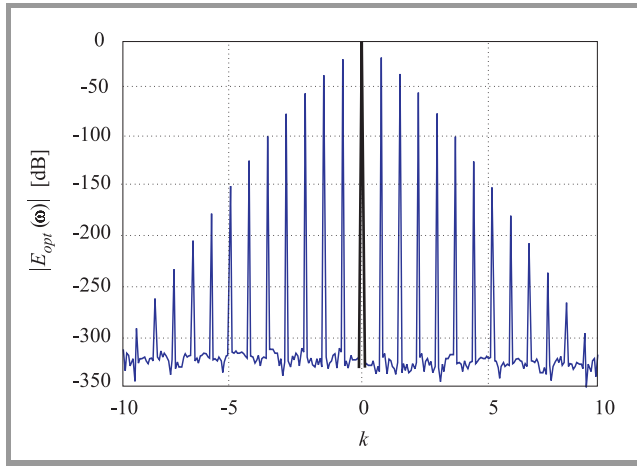


Fig. 9. MZM output field at bias for linear operation, $\alpha = 0.4$; $\gamma = 0.5$; $\omega = \omega_0 \pm k\omega_{RF}$.

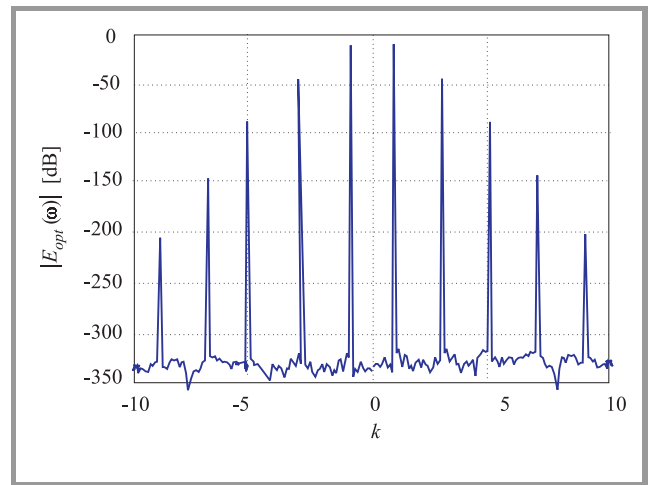


Fig. 11. MZM output field at bias for minimum transmission, $\alpha = 0.4$; $\gamma = 1$; $\omega = \omega_0 \pm k\omega_{RF}$.

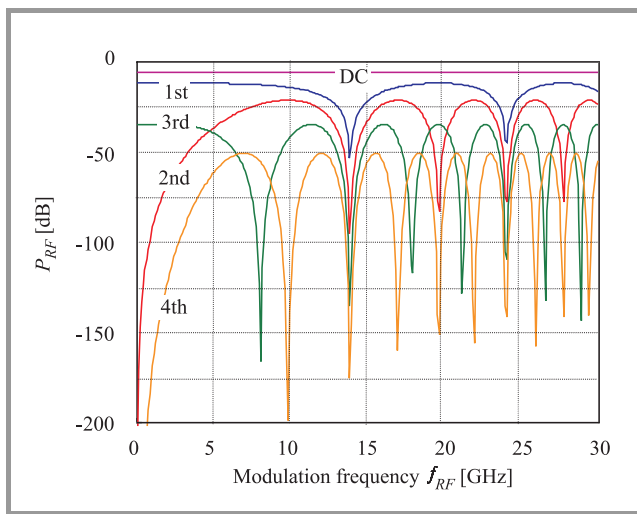


Fig. 10. Detected signals after propagation in dispersive fiber of $L = 19.2$ km, input field as in Fig. 9.

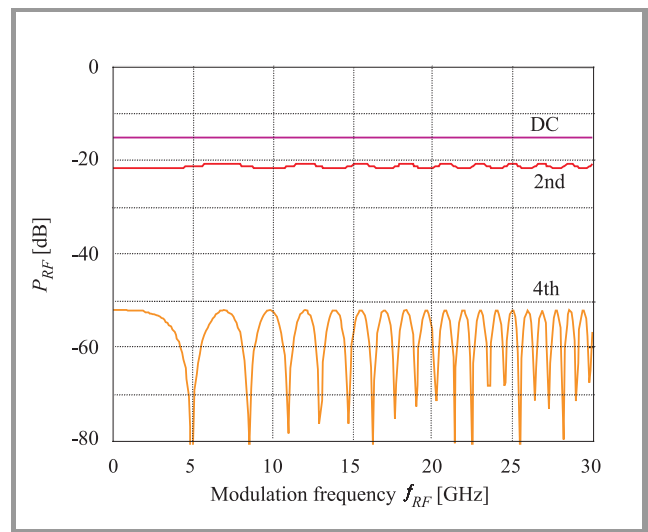


Fig. 12. Detected signals after propagation in dispersive fiber of $L = 19.2$ km, input field as in Fig. 11.

phase of the fundamental, second harmonic has two times, third harmonic has three times more rejections between two rejections of the fundamental. We note that this phenomena cannot be explained by the incoherent model of the MW optical link.

On the other hand, if the MZM is biased for minimum transmission (Fig. 11), the second harmonic of the modulation signal is not rejected, even after propagation in a nearly 20 km dispersive fiber (Fig. 12). In this case the phase difference cannot create complete rejection, since the optical carrier is suppressed. The advantage of the method is that only the subharmonic of the desired MMW signal is desired to drive the optical modulator. The developed method is rather general, it is suitable for calculating the effect of fiber dispersion simultaneously with effect of modulator bias in external modulation and chirp of direct modulated laser diodes as well [13–15].

5. Conclusions

Effect of chromatic dispersion on optical transmission of digital baseband signals is well described in the literature. However, for analogue MW/MMW IM/DD optical links chromatic dispersion has not been fully analyzed yet. In this paper MW harmonic generation in IM/DD fiber-optical links is discussed. The influence of chromatic dispersion on the optical transmission of MW/MMW signals in standard single mode fibers has been also examined. It was pointed out that standard SMF links operating at $\lambda = 1550$ nm cannot be used for transmission of MW/MMW signals without encountering the effect of chromatic dispersion. It was shown that dispersion penalty significantly limits the transmission distance in IM/DD optical links operating above 10 GHz. A several km long fiber-optical link filters the transmitted MW or MMW signal. As a function of fiber length L rejections are periodic and these periods are shorter and shorter as the modulation frequency f_{RF} is increased. First analytic explanation of the problem was given. Chromatic dispersion results in a difference between phase states of optical IM field sidebands. These sidebands are beaten coherently on the photodetector. As introduced in Eq. (13) as soon as the phase difference approaches π the modulation signal is lost. Then we presented a general model to calculate the harmonic levels and the effect of chromatic dispersion numerically. By the presented coherent model detected harmonics are estimated. To avoid chromatic dispersion problems, one might propose tailoring the fiber length exactly at the maxima of the penalty function shown in Fig. 8. As we demonstrated in Fig. 10 the locations of these maxima do not depend only on the fiber span but also on the IM frequency. Furthermore, temperature dependence, aging and polarization mode dispersion should be considered too.

Acknowledgments

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Attila Hilt graduated in electrical engineering at the Technical University of Budapest, Hungary in 1990. In 1989 he joined the Research Institute for Telecommunications (TKI Rt., presently called the Innovation Company for Telecommunications), Hungary. He worked on the design and development of microwave, millimeter-wave and optical circuits and systems. His research interests include various communication systems, MW and MMW photonics, combined optical-wireless and GSM systems. He received his Ph.D. degree in optics, optoelectronics and microwaves

from the Institut National Polytechnique de Grenoble (INPG), France in May 1999 and from the Budapest University of Technology and Economics in September 2000. Until 1999 he headed the Communications Test Laboratory of TKI. In 2000 he joined NOKIA Hungary as Sr. transmission network planner. He is involved in the design of Vodafone's nationwide GSM access network in Hungary. He is currently leading a research contract on high speed optical receivers at the Microwave Telecommunications Department of the Budapest University of Technology and Economics. He is an author/co-author of more than 50 papers presented in conferences or published in scientific journals. He is a member of the IEEE MTT and Communications societies.

e-mail: attila.hilt@nokia.com

Nokia Hungary Kft.

H-2040 Budaörs, Szabadság út 117./B.

Atronyx House, 5th floor.

BMGE-MHT, Budapest University

of Technology and Economics

Dept. of Microwave Telecommunications

H-1111 Budapest

Goldmann György tér 3. V2 épület, Hungary