HARMONIC DISTORTION IN DISPERSIVE FIBER - OPTICAL TRANSMISSION OF MICROWAVE SIGNALS

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Abstract : Dispersion penalty has been investigated widely in 1550nm fiber-optical links transmitting microwave (μW) signals. However, less attention was addressed to the levels of harmonics. This paper presents theoretical and experimental results on estimation of harmonics in the transmission.

I. INTRODUCTION

Radio-frequency signal transport through optical fibers gained significant interest in the last decades due to several perspective applications [1]. When using standard single-mode optical fibers (SMF) at 1550 nm for such systems a major limiting factor is dispersion. The basic phenomenon of fiber dispersion penalty in optical transmission of μW or millimeter-wave (mmW) signals has been published first in [2]. To the authors' knowledge, it has been first demonstrated experimentally by [3]. Later several dispersion compensation methods have been proposed [4-13]. Fig.1 shows measured transmission curve as a function of intensity modulation (IM) frequency. The curve belongs to 60 km SMF length. As seen in the figure, this link length resulted in transmission zeros at around 7.677, 13.462 and 17.578 GHz.

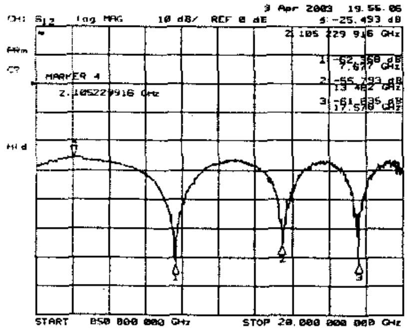

Fig.1. Dispersion penalty as a function of modulating μW frequency. $L = 60$ km.

The output optical spectra of either direct modulated lasers or external optical intensity modulators contain satellite peaks around the optical carrier [11-13]. At very high IM frequencies falling into the μW or mmW range, these satellite peaks have a frequency separation in the orders of 10 GHz or beyond. They propagate with different speed in the optical fiber due to chromatic dispersion. At $\lambda=1.55$ μm the typical dispersion value of standard SMF is about $D=17$ ps/nm/km. As a result, depending on the fiber length and the IM frequency, a complete rejection of the modulation content can happen. The detected power is given as [2-4] :

$$P_{RF}^{[dB]} \propto 20\log\left|\cos\left(cD\pi L\left(f_{RF}/f_{opt}\right)^2\right)\right| . \quad \text{Eq.1.}$$

II. NUMERICAL ANALYSIS OF OPTICAL TRANSMISSION AND HARMONICS

In the analysis usually an approximated case of only three spectral lines of optical field $E(\omega)$is assumed at the fiber input. This simplification reduces significantly the calculation difficulties and it is possible to derive the result of Eq.1 analytically. In the general case however, several optical field spectral lines are present at the fiber input. At the detection side amplitude and phase of these optical field spectral components are determined by the optical transmitter (LD or external modulator) as well as by parameters of propagation in the dispersive fiber. Only coherent models can explain properly the exact detected levels of different harmonics of the μW modulation signal. In this paper based on the coherent model of the μW optical link we simulate the effect of chromatic dispersion in the general case of several spectral lines. In coherent models the calculation is based on the optical field and not on the optical intensity. But for simplicity fiber birefrigence is neglected now.

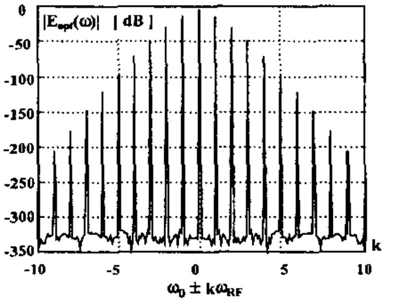

Fig.2. MZM output field at DC bias for linear operation, $\gamma = V_{DC}/V_\pi = 0.5$, $\alpha = V_{RF}/V_\pi = 0.4$.

Fig.2 shows the optical field amplitude calculated at the Mach-Zehnder Modulator (MZM) output biased at quadrature. Based on this optical field launched into the fiber, Fig.3 presents simulation results of harmonic evolution in dispersive optical transmission [14]. As seen in Fig.3, second harmonic is generated due to propagation in dispersive fiber. (Fiber, modulator and photodetection losses are neglected by normalization.) According to the measured results of Fig.1, the transmission is distorted by rejections at specific modulation frequencies.

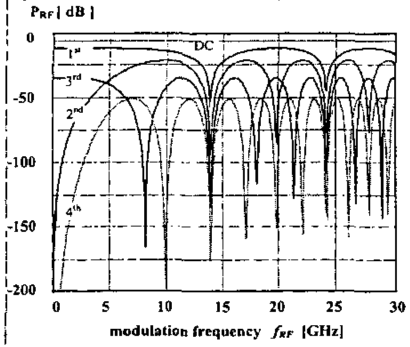

Fig.3. Detected signals after propagation in dispersive fiber of L=19.2 km, input field as Fig.2.

When the MZM is biased for linear operation, there are only odd components present in the optical intensity [12]. However, in the optical field both even and odd spectral components are present (Fig.2). When this optical field is launched into a dispersive SMF, due to dispersion even intensity components will appear after propagation. Calculated levels of harmonics are shown in Fig.3. Since phase of harmonics are rotated faster in the fiber than phase of the fundamental, second harmonic has two times, third harmonic has three times more rejections between two rejections of the fundamental. As mentioned these phenomena cannot be explained by incoherent models of the µW optical link [2-9, 11-13, 15-18].

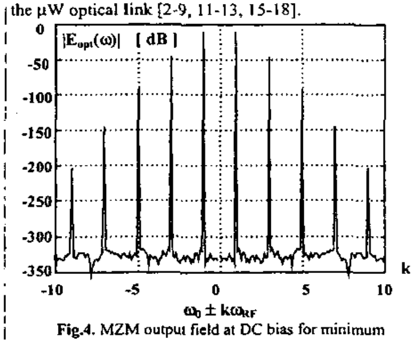

Fig.4. MZM output field at DC bias for minimum transmission, $\gamma = V_{DC}/V_\pi = 1$, $\alpha = V_{RF}/V_\pi = 0.4$.

On the other hand, if the MZM is biased for minimum transmission (Fig.4), the second harmonic of the modulation signal will not be rejected, even after propagation in a nearly 20 km dispersive fiber (Fig.5). The reason of this phenomenon is the coherent beating at the photodetector, explained previously [15]. In this case the phase differences cannot create complete rejection, since the optical carrier is suppressed. As an advantage of the method only the subharmonic of the desired mmW signal is required to drive the optical modulator.

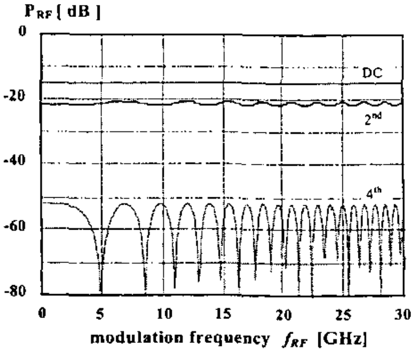

Fig.5. Detected signals after propagation in dispersive fiber of L=19.2 km, input field as Fig.4.

Based on the idea presented in Fig.4-5 different optical methods are investigated to overcome the effect of chromatic dispersion. Self-heterodyning techniques, dual mode lasers and optical single sideband (SSB) modulation are proposed. These solutions are described in the literature in details. [3-9]

III. EFFECTS OF MODULATOR TYPES AND BIAS SETTINGS

The developed simulation method is rather general. Therefore it is suitable for calculating the effect of fiber dispersion simultaneously with effect of modulator bias in external modulation or chirp of direct modulated laser diodes [12, 13, 15]. The push-pull MZM and its possible cross sections [19] are shown in Fig.6.

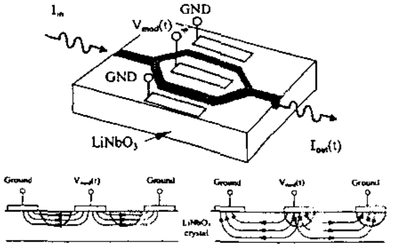

Fig.6. Push-pull MZM. Possible cross sections of push-pull MZ modulators having symmetric CPW electrodes.

Fig.7 presents calculated level of the signal detected at fundamental frequency as a function of fiber length L and modulation frequency f_{RF}. Normalized bias voltages are denoted as $\gamma = V_{DC}/V_\pi$ and $\alpha = V_{RF}/V_\pi$. Compared to the fiber penalty plot of Fig.3 now optical losses due to modulation as well as detection have been introduced in the model (linear fiber loss is still neglected).

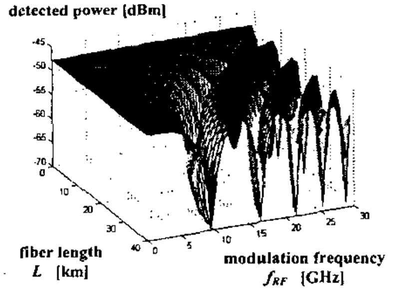

Fig.7. Detected power level of μW signal transmitted optically in dispersive fiber. (Linear modulator bias of $\gamma=0.5$, $\alpha=0.25$, D=17ps/km/nm, photodiode responsivity : R_{PD}=0.35 A/W)

Another possible MZM electrode configuration is shown in Fig.8. As seen in the left cross section, also unbalanced operation is possible in this case. This difference from the previous push-pull MZM results in a higher level of modulator chirp. This "single-arm" modulation gives different output optical field than that of the push-pull MZM presented in Fig.6.

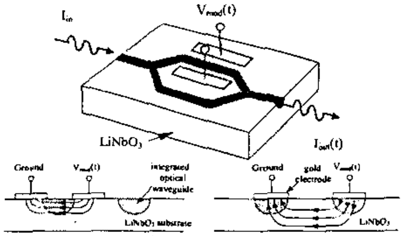

Fig.8. Asymmetric CPW electrode MZ modulator and its possible cross sections : unbalanced and push-pull operation.

Fig.9. shows again the calculated level of the signal detected at fundamental frequency as a function of modulation frequency f_{RF} and fiber length L.

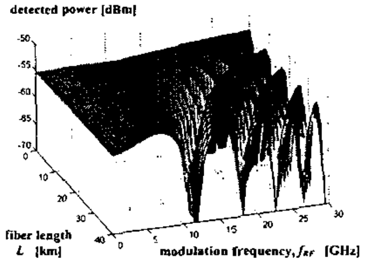

Fig.9. Dispersion compensation by the chirp of the unbalanced (one arm modulated) MZM.

Compared to Fig.7 the frequency of the first rejection is a bit increased in Fig.9 and a slight overshoot can be seen before it [17, 18]. It is due to the combined effect of modulator chirp and fiber dispersion [20].

IV. EXPERIMENTAL RESULTS

Fig.10 shows the experimental setup. Detected levels of fundamental, second and third harmonics have been measured. The frequency of the signal source modulating the optical transmitter and the center frequency of the spectrum analyzer have been set simultaneously by a measurement control and data acquisition software.

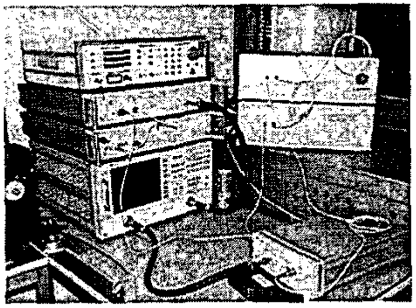

Fig.10. Photograph of the experimental setup for the fundamental

Different fiber lengths of 10, 20, 30, 40, 50 and 60 km have been tested. Fig.11 shows fundamental and harmonic levels measured on a 40 km long fiber.

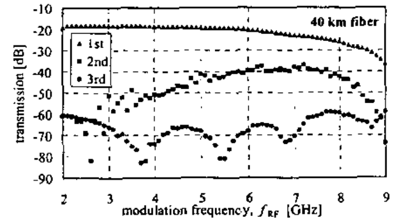

Fig.11. Measured levels of fundamental, second and third harmonics. L=40 km.

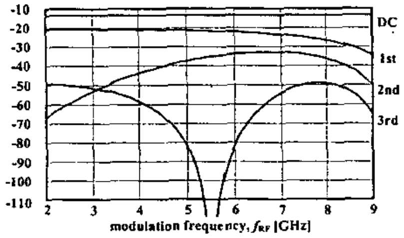

Fig.12. Simulated results for L=40 km long fiber. (push-pull MZM, γ=0.5, α=0.3, D=17ps/km/nm)

Fig.12 plots the corresponding simulated results. As seen in the figure, fundamental and second harmonic levels were correctly calculated. However, for the third harmonic, more transmission zeros were measured. This requires a further investigation in the depth of modeling *as well as in the measurement procedure. Such effects as* polarization state between the optical source and the MZM, polarization mode dispersion, spectral purity of the signal source (multitone modulation at the MZM) or more accurate calibration in the measurements must be considered. Fig.13 and 14 show the levels measured and simulated over a 50 km long fiber, respectively. Now the *MZM driving electrical signal itself was composed of* three tones, the fundamental and its 2nd and 3rd harmonics.

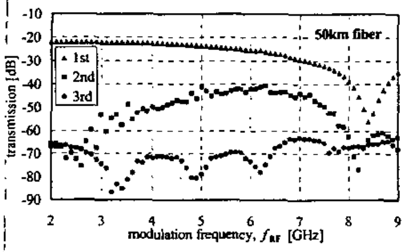

Fig.13. Measured levels of fundamental, second and third harmonics. L=50 km.

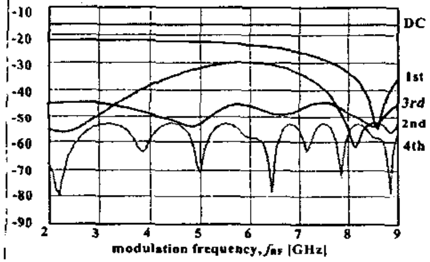

Fig.14. Simulated results for L=50 km long fiber. (push-pull MZM, γ=0.5, α=0.4, f_2/f_1:0.07, f_3/f_1:0.05, D=17ps/km/nm)

VI. CONCLUSION

Distortion levels of harmonics have been investigated in fiber-optical transmission of μW/mmW signals. Second harmonic generation of modulation signals in the optical path has been verified theoretically and experimentally. We presented a general model to calculate harmonic levels and the effect of chromatic dispersion numerically. Levels of detected harmonics are estimated by the developed coherent model. Experimental examples have shown clearly the presence and evolution of harmonics in the μW photonic link. It was shown that these harmonics also exhibit minima and maxima due to fiber dispersion.

VII. ACKNOWLEDGMENTS

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