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SPECTRAL TRANSMISSION CHARACTERISTICS OF ANDVANCED AMPLITUDE MODULATION FORMATS

In this paper we focus our attention on numerical investigation of high-order amplitude modulation format in single-channel transmission systems utilizing different kinds of optical fibers. The aim is to show the spectral behavior of advanced amplitude modulated signals in view of fundamental parameters of fiber-optic system. The investigation is realized by solving the nonlinear Schrodinger equation (NLSE) through the pseudospectral split-step Fourier method (SSFM). The obtained results show that the advanced amplitude modulation formats are sensitive to nonlinear phenomenon and they are more desirable for using at short-haul networks.

Keywords: *Amplitude modulation format, nonlinear Schrodinger equation, split-step Fourier method, optical communication system.*

1. Introduction

In general, the implementation of novel kinds of modulation formats follows the goal of increasing the system capacity and improves the spectral efficiency of currently used fiber optic transmission systems. The most popular transmission modulation technique has been on-off keying (OOK) over the years, in which the optical power is modulated according to incoming sequence of bits [1, 2]. The major drawback of OOK format is that it enables to transmit only one information bit per symbol. On the other hand, the advanced modulation techniques allow transmission of several information bits per symbol and so they fulfill the mentioned requirements for the future fiber-optic communications [2, 3].

From a wide range of novel types of high-order modulation formats [1–3], our investigation is oriented to high-order amplitude formats, usually denoted as M-ary amplitude shift keying (*M*-ASK). This modulation format represents the simplest modulation technique from a point of view of transmitter structure [3]. *M*-ASK modulation scheme provides good choice for capacity enhancement of short-haul networks [4, 5] or serves for conversion application between non-return-to-zero (NRZ) and return-to-zero (RZ) format [6].

2. Theory

In general, the high-order modulated signals at the output of an optical transmitter have complex nature and can be described as follows [1, 7]:

$$E_m(t) = \Re e\{A_m(t)\cdot e^{j\omega_0 t}\} \tag{1}$$

where $E_m(t)$ denotes a modulated optical field, $A_m(t)$ is a modulated complex envelope with Gaussian shape and ω_0 is optical carrier frequency. The *M*-ASK modulated complex envelope of optical field can be expressed by [1, 3]:

$$A_m(t) = A_0 \cdot \sum_{i=0}^{N_s} S_k^{ASK} \cdot A(t - i \cdot T_s) \tag{2}$$

where N_s is the number of transmitted symbols, A_0 is the envelope amplitude, T_s is symbol interval proportional to the symbol rate R_s and S_k^{ASK} represents a complex amplitude symbol chosen from a discrete alphabet of elements corresponding to the number of modulation states *M*.

Due to the complex nature of high-order modulation formats, its representation is always illustrated in a complex plane as the superposition of in-phase (*I*) and quadrature (*Q*) component. The constellation diagrams for *M*-ASK modulation formats are depicted in Fig. 1.

The fundamental equation for studying the pulse evolution in fiber–optic transmission system is so-called nonlinear Schrodinger equation NLSE [8], which includes the impact of various fiber degradation mechanisms on transmitted optical signals. The NLSE can be expressed in the following form [7, 8]:

$$\begin{aligned}\frac{\partial A_m}{\partial z} &= j\gamma|A_m|^2 A_m - \frac{\alpha}{2}A_m - \beta_1\frac{\partial A_m}{\partial t} - \\ &- j\frac{\beta_2}{2}\frac{\partial^2 A_m}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 A_m}{\partial t^3},\end{aligned} \tag{3}$$

where β_1 is related to the group velocity, β_2 is the group velocity dispersion (GVD) parameter, β_3 is the third-order dispersion parameter, α is the fiber attenuation and γ is the nonlinear coefficient

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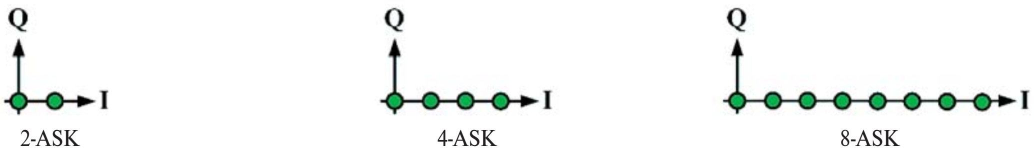


Fig. 1 Constellation diagrams of M-ASK modulations

of optical fiber. A_m is a modulated complex envelope carrying the encoded information in a given number of amplitude levels.

From a numerical point of view there are several options how to solve the NLSE, which only has the nontrivial solution. The most desirable numerical approach is so-called Beam Propagation Method (BPM) [7] in two widely used algorithmic expressions; the Finite Difference Method (FDM) [7, 9] and Split-Step Fourier method (SSFM) [3, 7, 8]. For our investigation, the SSFM technique was used. The SSFM is based on solving the NLSE in two separated parts according to the degradation effects. The linear and nonlinear impairments are solved in a small step in spectral and in time domain, respectively. The algorithmic implementation and operational principle of SSFM is shown in Fig. 2.

3. Results and discussion

The employing of advanced modulation formats into the fiber-optic system brings novel issues into the pulse propagation. After a modulation process, the optical pulses obtained new properties corresponding to the type of digital modulation and actual transmitted pulse. In context of *M*-ASK signals, this means that the transmitted pulses have different levels of amplitudes, so the propagation is quite different in comparison with the traditional power scheme OOK. The fact of various amplitude levels of transmitted pulses leads to the different sensitivity to the nonlinear phenomenon of self-phase modulation (SPM), whose impact on pulses is the limiting factor from the point of spectral broadening in a single-channel system.

In Fig. 3 are depicted the average values of spectral broadening depending on the fiber length of 2-ASK, 4-ASK and 8-ASK signals with input power $P_{in} = 1$ mW and bit rate $R_b = 10$ Gbps at $\lambda = 1550$ nm for two types of optical fibers; Standard single-mode fiber (SSMF) [10] and Dispersion shifted fiber (DSF) [11], respectively.

It is obvious that the value of spectral broadening is rapidly growing with a higher number of amplitude modulation levels. The worst results were obtained for 8-ASK format, for which the spectral broadening is significantly larger for both fiber types. For low-order amplitude levels (2-ASK and 4-ASK), the role of linear transmission properties (attenuation and chromatic dispersion) influence the impact of nonlinear SPM in sense of balancing the strength of signal degradation, especially after the effective fiber length, after which the impact of chromatic dispersion becomes the dominant factor of degradation and the growth of spectral broad-

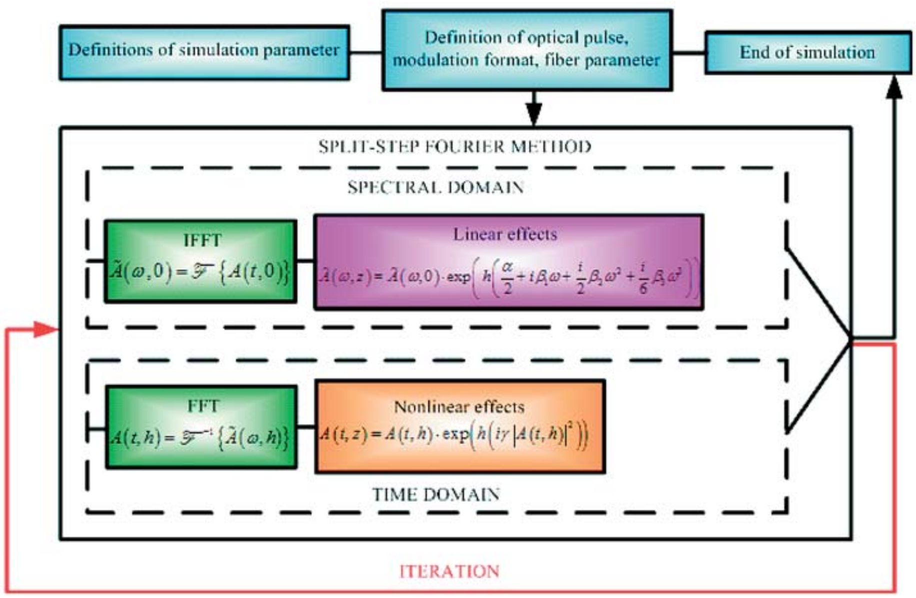
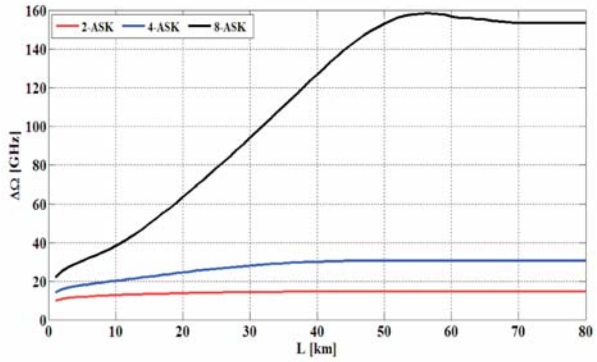
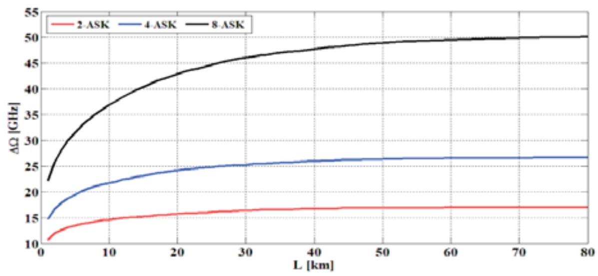


Fig. 2 Algorithm of split-step Fourier method

ening is significantly slower with a further increasing fiber length. From a transmission point of view, the DSF fibers exhibit considerably lower spectral broadening in comparison with SSMF fibers.



a) SSMF

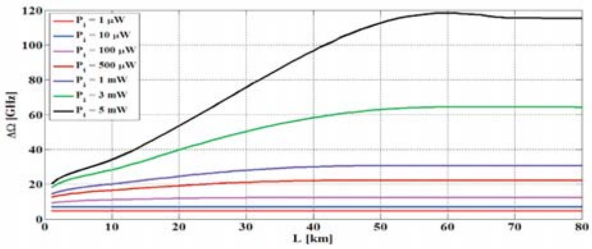


b) DSF

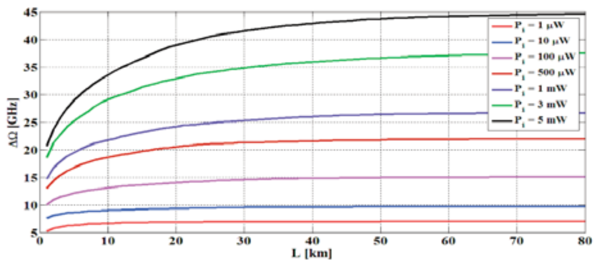
Fig. 3 Spectral broadening of different M-ASK signals

3.1 Effect of input power

In Fig. 4 can be seen the evolution of spectral broadening depending on the fiber length for various levels of input powers of 4-ASK signals with the same bit rate of system $R_b = 10$ Gbps at operating wavelength $\lambda = 1550$ nm for two types of optical fibers; SSMF 4a. and DSF 4b., respectively. The sequence of simulated symbol was generated with the same probability. It can be observed that for lower values of input powers, the spectral broadening is nearly constant or increases very slowly for both types of used optical fibers. The using of lower powers should be therefore recommended for implementation of *M*-ASK modulation in a fiber-optic system. The transmission symbols, which are encoded into the higher power levels represent larger and main contributions to the resulted effect of spectral broadening, when the higher value of power was launched into the fiber. We can also see that DSF fibers exhibit better robustness against nonlinear SPM degradation for a wider range of fiber lengths in comparison with SSMF fibers for the same input power levels. For this reason, the SSMF fibers should be used in a transmission system for shorter transmission distances with higher power levels. On the other hand, by using DSF fibers, it is possible to reach longer transmission distances with good spectral performance or the transmission system can operate with higher powers resulting in longer distance reach.

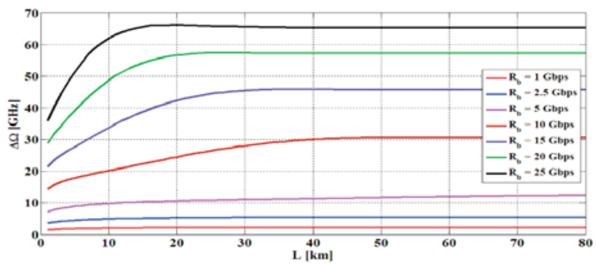


a) SSMF

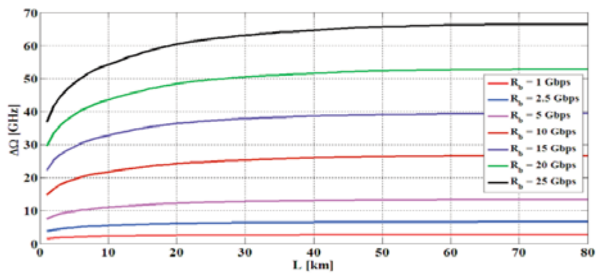


b) DSF

Fig. 4 Spectral broadening of 4-ASK modulation



a) SSMF



b) DSF

Fig. 5 Spectral broadening of 4-ASK modulation

3.2 Effect of bit rate

In Fig. 5 are illustrated the dependences of value of spectral broadening on the fiber length with various values of total bit rate Rb with the same moderate input power $P_{in} = 1$ mW for SSMF and DSF optical fibers.

From Fig. 5 an interesting fact can be observed. If the values of bit rates of an optical transmission system are higher, the spectral transmission performance of SSMF fibers is better. At lower bit rates ($<$ 10 Gbps), the value of spectral broadening is nearly insignificant and with using longer fiber lengths, it increases in a slow way. On the other hand, at higher bit rates ($>$ 10 Gbps), the resulted spectral broadening exhibits growing nature, but not as large as in the case of increasing power. The reason is that shorter optical pulses (higher bit rates) are more influenced by the effect of chromatic dispersion, which balances the impact of SPM. On the other hand, for DSF fibers this fact is not so obvious due to a very low (nearly zero) value of chromatic dispersion at an operating wavelength. From this point of view, the spectral transmission performances of SSMF and DSF are comparable.

For higher bit rates, the amplitude modulation formats provide suitable choice for implementation in a fiber-optic system, which is in good agreement with requirements for the next generation optical system.

4. Conclusion

In this paper we numerically investigated the M-ASK modulated signals. It was shown that the optical signals, which employ novel multilevel amplitude formats, are sensitive to the nonlinear effect of SPM in the sense of increasing the value of spectral broadening. The most promising and suitable amplitude format seems to be 4-ASK for SSMF and DSF fibers at moderate powers and bit rates. The power dependence of transmission pulses sets the significant limit for long-haul application, so the short-haul distance applications are preferred. On the other hand, by using the shorter duration of optical pulses, the desirable performance of a fiber-optic system in sense of balanced interaction between chromatic dispersion and SPM for both types of investigated fibers may be achieved.

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