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SIMULATION OF PHOTONIC DEVICES – OPTICAL FIBRES

I. Bibac

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Driven by the rapid increase in Internet use and the introduction of applications like digital television and videoconferencing, the demand for a significant increase in bandwidth is growing at an unparalleled rate. Essential to making any increase in capacity a reality are the optical fibre, the key element and the enabler of DWDM - Dense Wavelength Division Multiplexed - systems. Also the fibre optic is the most important element that contributes to design an Optical Internet network. An Optical Internet [1] is defined as any Internet network where the network link layer connection are "dedicated" wavelengths on an Wave Division Multiplexed optical fibre directly connected to a high performance network router. The high performance network router replaces traditional ATM – Asynchronous Transmission Mode - and SDH – Synchronous Digital Hierarchy switching and multiplexing equipment in that it is the essential statistical multiplexing device that it is the essential statistical multiplexing device that controls wavelength access, switching, routing and protection. The present article will presents some simulations [4] for an optical fibre – modelling of Raman scattering in a fibre NLS – Non-linear Dispersion Fibre module and the polarisation mode dispersion in a single fibre optics.

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1. Introduction

There are three types of single mode optical fibres, which are characterised by their primary spectral window 850-nm, 1310-nm and 1550-nm respectively.

For long haul networks 1550-nm fibre is the most common as the EDFAs (Erbium Fibre Doped Amplifiers) operate in a small part of the 1550-nm operating window.

There are three types of 1550-nm fibre – No dispersion-shifted fibre - NDSF, dispersion-shifted fibre - DSF, non -zero dispersion shifted fibre - NZDSF or lambda-shifted fibre.

The design of photonic systems has reached a stage where simulation is no longer a luxury, but a necessity.

This article describes the simulation of a single mode fibre respectively: the polarisation mode dispersion in single fibre optics and the modelling of Raman scattering in a fibre NLS module.

2. Theory

2.1. Signal representation for interconnecting models

The simulations were done based on the PTDS (Photonic Transmission Design Suite) – software simulator produced by Virtual Photonics Inc (www.virtualphotonics.com).

Two modes of simulation exist in PDTS***: sample mode and block mode***. *Sample Mode* is used for bi-directional simulation of closely coupled components. *Block Mode* passed data as arrays of the complex envelope of the optical field; restricting bidirectionality to components spaced by more than a block length, such as optical switches separated by fibre [2].

Sample mode has a single signal representation, covering all simulated optical frequencies and assuming a single polarisation.

Block mode has both sampled and statistical signals, containing polarisation information and centre frequency, allowing a simulation to be portioned spectrally into appropriate signal representations as follows.

- A single frequency band **(SFB)** can be used to cover all data channels, or individually using multiple frequency bands **(MFB's),** each with a centre frequency and each covering one ore more channels.
- Noise Bins **(NB's)** represent broad noise spectra efficiently as a mean power spectral density within a defined frequency range. NB's are effective for the amplified spontaneous **(ASE)** in an optical amplifier.

The fibre models are based on the split-step Fourier method, in which the fibre is divided into sections. In each section, the effects of dispersion and nonlinearly are treated separately [2].

The dispersion is treated in the frequency domain as a frequency-dependent phase shift, and the nonlinearly in the time domain, as a phase shift dependent instantaneous power [2]. All signal representations are converted into a single sampled signal, covering the whole wavelength range (fibre NLS module).

Split-step Fourier method is the most important method to solve the single and multi-channel pulse-propagation problem in lossy non-linear dispersive media.

The equation which describes the amplitude of the propagation signal A is:

$$(\nu/\nu z)\underline{A} = (\underline{D}+N)\,\underline{A} \tag{1}$$

where $\underline{A}$ describes the amplitude of the propagating signal, $\underline{N}$ is the non-linear operator which takes into account fibre nonlinearities and $\underline{D}$ is the linear operator that covers the loss and dispersion.

Currently, non-linear and linear effects act simultaneously along the propagation direction. The idea is to act independently in order to obtain an approximate solution for the propagating field.

In fact, taken into account a small step h in distance, the propagation from point z to point z+h is computed in two steps, in the first one only the nonlinearities acts and in the second one only the linear effects acts [3].

$$\underline{B}\,(z, T) = \exp\,(h\underline{N})\;\underline{A}\,(z, T) \tag{2}$$

$$\underline{A}\,(z, T) = \exp\,(h\underline{D})\;\underline{B}\,(z, T) \tag{3}$$

The first step can be done in the time domain and the second in the frequency domain.

The final equation can be write:

$$\exp\,(h\underline{D})\;\underline{B}\,(z, t) = B\,(z, t)\,F^{-1}\,\{\exp\,[h\,D\,(j\omega)]\,F\,[B\,(z, T)]\} \tag{4}$$

where F denotes the operation of Fourier transform. The numerical calculation of equation (4) can take advantage of modern FFT algorithms.

2.2. Polarisation mode dispersion in a single fibre optics

The single-mode glass fibre is most important component used in a fibre – based optical transmission system. The effects that have to be considered can be classified [2]:

Linear effects:

- Attenuation
- Chromatic dispersion
- Polarisation mode dispersion (PMD).

Non-linear effects:

- Non-linear refraction
- Self-phase modulation
- Cross-phase modulation

- Four-wave mixing
- Stimulated Raman scattering
- Stimulated Brillouin scattering

Additionally to chromatic dispersion and fibre nonlinearities, polarisation dispersion can disturb the transmitted lightwave.

In order to estimate the effect of polarisation, the PMD module propagates two polarisations represented by coupled non-linear Schodinger equations.

At each step of the split-step Fourier algorithm, the polarisations are scattered randomly on a Poincaré sphere, with a uniform distribution of polarisations. This distribution will give an increase in pulse spreading, which tends to be proportional to the square root of the propagation distance [2].

The simulation depicts the PMD effects in the time domain by an eye diagram as well as by a comparisation of x- and y- polarised signal parts after transmission.

The **fibre length** is set to **200 km**, the **bit rate to 10x10^9 bit/s** and the simulation is done in case we have PMD.

2.3. Modelling of Raman scattering in a fibre NLS module

Stimulated Raman Scattering **-** SRS [2] refers to a process, whereby a photon of the originating field is annihilated to create a lower-energy photon at the downshifted Stokes frequency and an optical phonon with the appropriate energy and momentum to conserve the overall energy and the overall momentum.

The presence of Raman gain in optical fibres has important consequences for the design of WDM – systems. Since SRS is an extremely broadband effect – the SRS bandwidth is about 12 THz at 1.5 μm – SRS couples different channels in WDM systems and gives rise to significant non-linear crosstalk.

The Raman effects can be rapidly estimated using parametrized signals and semi-analytical techniques. The module used for the fibre is the NLS Frequency-decomposition module, which allows control of the modelling of non-linear interactions between different frequency types and is useful for identifying the cause of degradation in a system.

3. Experimetal setup

3.1. Polarisation mode dispersion in a single fibre optics – experimental set-up

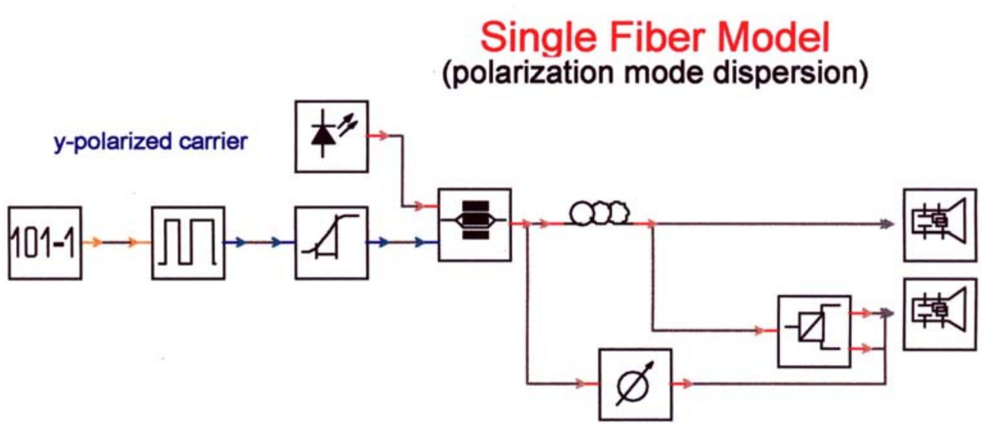

Fig. 1. Polarisation mode dispersion set-up model.

The experimental arrangements in order to show the effects of PMD into a fibre optic is presented schematically in Fig. 1 [3].

The fibre module can take into account the polarisation effects and to have a realistic treatment of the PMD effects we used a random fluctuation of birefringence. We have taken into account also the four-wave mixing (FWM), self-phase modulation (SPM), cross-phase modulation (XPM), first order group-velocity dispersion (GVD), second order GVD and attenuation of the fibre.

The PRBS module generates pseudo random binary sequences at 2.5 Gbit/s, BER = 10^{10}bit/s which is passed through a NRZ (**N**on **R**eturn to **Z**ero) module. The resulting signal is transmitted to a Gaussian filter that transform rectangular electrical input pulses into smoother output pulses with a user-defined rise – time – 0.25/Bit rates.

The continuous wave (CW) optical signal produces by laser CW module is pumped together with the output pulses from PBRS generator into a Mach-Zehnder modulator and then into the fibre NLS_PMD module. The Mach-Zehnder module has an extinction ratio equal to 30 dB and a symmetry factor equal to –1.

To show the optical signals we used an Optical Spectrum Analyser – OSA. To avoid the saturation of OSA we used an atenuator in front of this at 20 dB. To display optical signal waveforms in the time domain we use a ViScope module that acts as a time domain visualiser for optical power signals. The Polarisation Beam Splitter module simulates an ideal polarisation beam splitter rotated through an angle θ. If θ=0 the Output X and Output Y ports correspond to the x- and y- polarisation components of the incident light, respectively.

The fibre optic has the following characteristic [3]:

- Reference frequency: 193×10^{12} Hz
- Length: 200km
- Attenuation: 0.2×10^{-3} dB/m
- Dispersion: 0.1×10^{-7}s/m^2
- Dispersion Slope: 8 s/m^3
- Non-linear Index: 2.6×10^{-20} m^2/W
- Core Area: 8×10^{-11} m^2
- Raman Coefficient: 0.3
- Polarisation Mode Dispersion: $5\times10^{-12}/31.62$ s/m$^{-1/2}$

The CW laser has the following characteristics [3]:

- Reference frequency: 193×10^{12} Hz
- Average power: 1 mW
- Noise dynamic: 3 dB

3.2. Modelling of Raman scattering in a fibre NLS module – experimental set-up

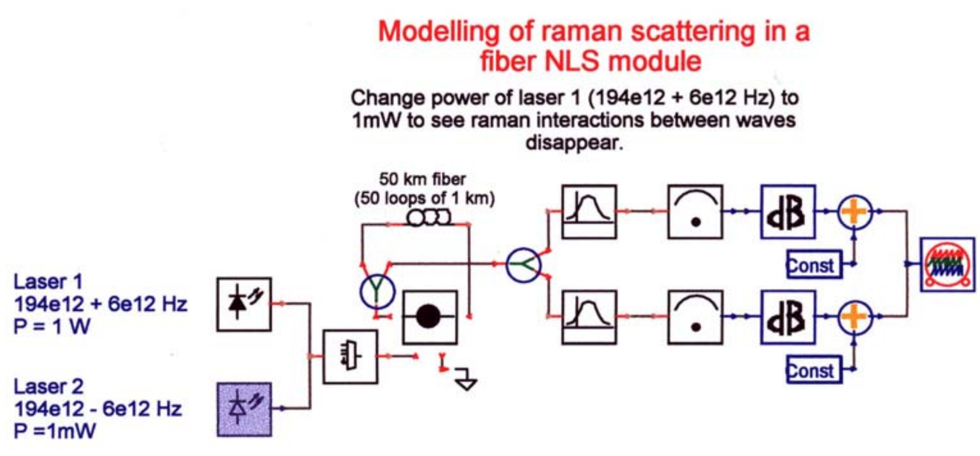

Fig. 3. Raman scattering in a fibre NLS module set-up model.

The experimental arrangements to have shown the Raman scattering in a fibre NLS module are illustrate in Fig. 2 [3].

The WDM MUX module multiplexes two optical WDM channels (laser 1 and laser 2) with an insertion loss equal to zero. The resulted signal is applied to **100 fibre loops of 1 km** and the final signal is passed through a Gauss filter (bandwidth = 10^{10} Hz) to the powermeter in order to measure the power.

The fibre optic has the following characteristic [3]:

- Reference frequency: 193×10^{12} Hz
- Attenuation: 2×10^{-4} dB/m
- Dispersion: 10^{-7} s/m^2
- Dispersion Slope: 80 s/m^3
- Non-linear Index: 2.6×10^{-20} m^2/W
- Core Area: 8×10^{-11} m^2
- Raman Coefficient: 0.3
- Polarisation Mode Dispersion: $5\times10^{-12}/31.62$ s/m$^{-1/2}$

By changing the power of laser 1 to 1 mW we see that the Raman interactions between waves disappear.

4. Discussion of the results

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4.1. PMD results

Below, two eye diagrams are shown which depict the influence of chromatic and polarisation mode dispersion as well as fibre nonlinearities on the relative eye opening. **The fibre length is set to 200 Km, the bit rate to 10^{10} bit/s.**

The first diagram – Fig. 4 shows that if PMD is added the relative eye opening decrease.

The second diagram – Fig. 5 shows effects of chromatic dispersion only.

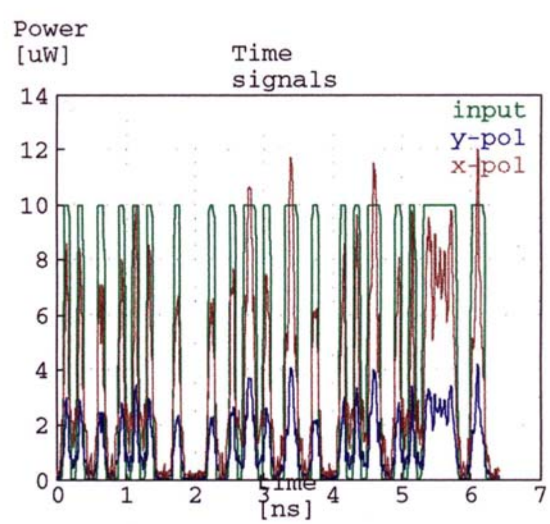

Fig. 4. Eye diagram in a PMD single fibre optic.

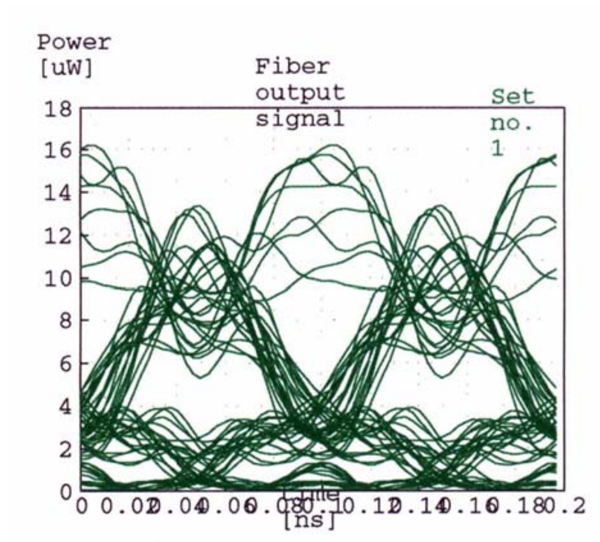

Fig. 5. Effects of chromatic dispersion in a PMD single fibre optic.

4.2. Raman scattering results

In the figures below changing the power of laser 1 to 1 mW we see that the Raman interactions between waves disappear (power of waves vs. propagated fibre lengths). The Raman gain varies linearly with frequency in the vicinity of the carrier frequency.

Fig. 6 shows the power of waves vs. propagated fibre length with Raman interactions.

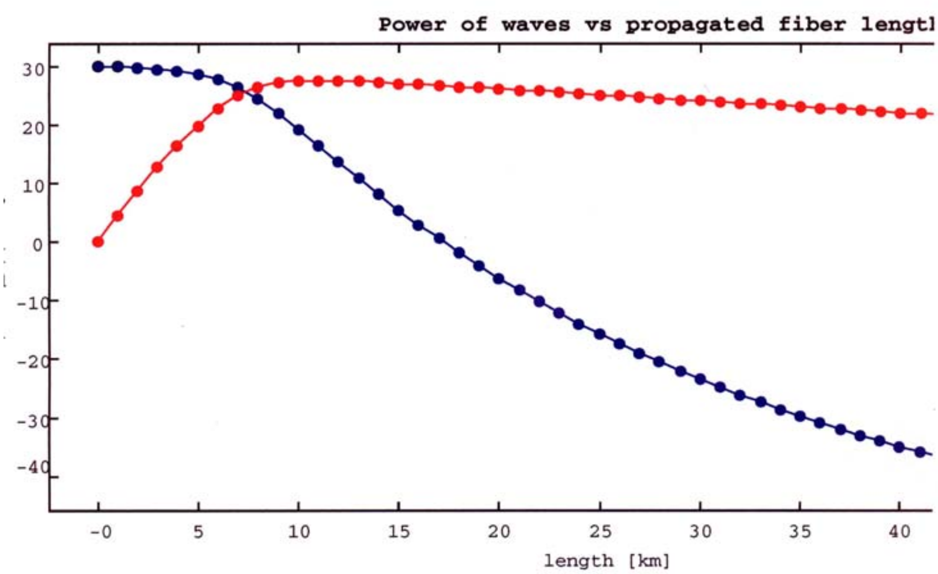

Fig. 6. Power of waves vs. propagated fibre length with Raman interactions.

Fig. 7 shown the power of waves vs. propagated fibre length without Raman interactions.

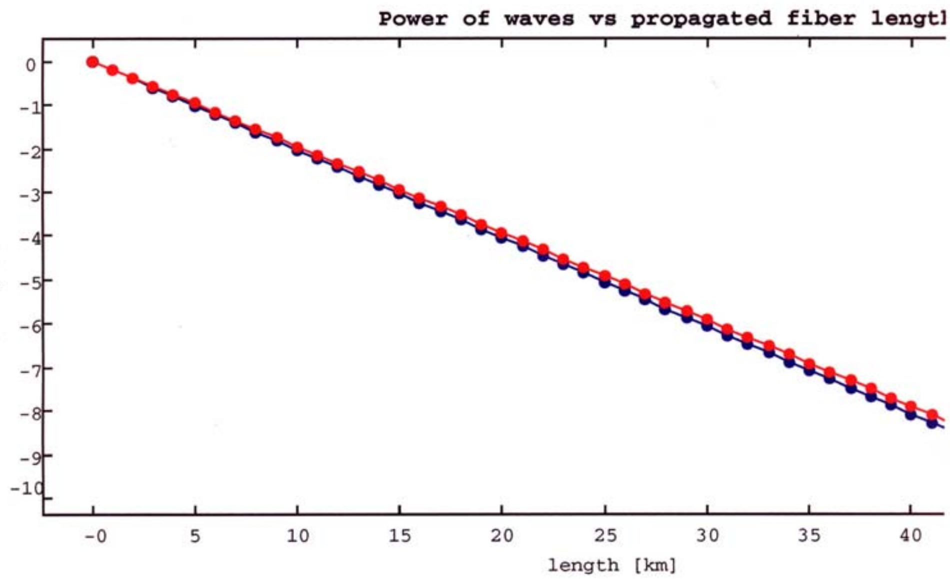

Fig. 7. Power of waves vs. propagated fibre length without Raman interactions.

5. Conclusions

Photonic system design requires simulation over a wide range of scales; this design considers the effects of the smallest components in order to create a global system.

Based on this tool we can simulate a fibre optic and to illustrate how the details of device performance can be efficiently considered within a large network simulation.

All the simulations were done based on the PTDS (Photonic Transmission Design Suite) – software simulator produced by Virtual Photonics Inc. PTDS is based on the Ptolemy simulation engine [5], with a proprietary graphical user interface and proprietary signal representations.

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