THEORY AND FUNDAMENTALS

Understanding the physical origin of surface modes and practical rules for their suppression

F.Poletti, E.Numkam Fukoua,

ECOC 2013, Paper Tu.3A.4

Predicting structural and optical properties of hollow-core photonic bandgap fibers from cane structural information

E.Numkam Fokoua, M.N.Petrovich, N.K.Baddela, N.V.Wheeler, J.R.Hayes, F.Poletti, D.J.Richardson

OFC 2013, paper OTh1J.1

Real-time prediction of structural and optical properties of hollow-core photonic bandgap fibers during fabrication

E.Numkam Fokoua, M.N.Petrovich, N.K.Baddela, N.V.Wheeler, J.R.Hayes, F.Poletti, D.J.Richardson

Optics Letters, 38 (9), 1382-1384 (2013)

Space-Division Multiplexing in Optical Fibres

D.J.Richardson, J.M.Fini, L.E.Nelson

Nature Photonics 2013 Vol.7(5) pp.354–362.

Expressions for the nonlinear transmission performance of multi-mode optical fiber

A.D. Ellis, N. MacSuibhne, F.C. Garcia Gunning, S. Sygletos

Optics express 21 (19), 22834-22846, 2013

A.D. Ellis, N. Doran, "Are few-mode fibres a practical solution to the capacity crunch?", Transparent Optical Networks (ICTON), 2013 15th International Conference on, paper TU.C2.1

Impact of power allocation strategies in long-haul few-mode fiber transmission systems

D Rafique, S Sygletos, AD Ellis

Optics express 21 (9), 10801-10809, 2013

Impact of mode coupling on the mode-dependent loss tolerance in few-mode fiber transmission

A. Lobato, F. Ferreira, M. Kuschnerov, D. van den Borne, S.L. Jansen, A. Napoli, B. Spinnler, B. Lankl

Optics Express 20 (28), 29776-29783, 2012

Optical Link Design for Minimum Power Consumption and Maximum Capacity

N.J. Doran, A.D. Ellis

ECOC 2013, Paper P4.9

The MODE-GAP project

A.D.Ellis

IEEE Photonics Conference (IPC), Paper 299445, (2013).

OSA Annual Meeting, Frontiers in Optics, 4-8th Oct 2012, Invited Paper in Category FiO5.4

Soliton Propagation in a Few Mode Optical Fibre

N. Mac Suibhne, R. Watts, S. Sygletos, F. Garcia Gunning, L. Grüner-Nielsen, A.D. Ellis

OECC 2012, paper SC3-3.

We experimentally demonstrate adiabatic soliton propagation in the fundamental mode of a few mode optical fibre and more complex behaviour in a higher order mode, indicating that the impact of nonlinearities differs for each mode.

http://dx.doi.org/10.1109/OECC.2012.6276540

The nonlinear Shannon limit and the need for new fibres

A.D.Ellis

Proc Photonics Europe, Nonlinear Optics and Applications VI, Paper 8434-16, (2012) *This paper will review the current understanding of the so called nonlinear Shannon limit, and will speculate on methods to approach the limit through new system configurations, and increase the limit using new optical fibres.*

http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CCYQFjAB&url=http%3A%2F%2Fproceedings.spiedigitallibrary.org%2Fdata%2FConferences%2FSPIEP%2F64930%2F84340H_1.pdf&ei=279RUK_SFIazhAeWs4Fg&usg=AFQjCNFY5f4WKhLwOk7--F43LEe8phtjvA&cad=rja

Current Capacity Limits and Activities within the EU Project MODE-GAP to Overcome them

A.D.Ellis

IEEE Summer topical meeting on Spatial Multiplexing, Plenary Paper (2012).

In this presentation we will discuss the implications of the so called Nonlinear Shannon Limit. We will compare technologies including new fibres for long haul transmission and techniques to expand the capacity of existing standard single mode fibres.

http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6280717

Capacity Limits of Optical Fibre Based Communications

Jian H. Lin, Andrew Ellis, and Danish Rafique

Proc Signal Processing in Photonic Communications (SPPCom), Toronto, Canada, Paper SPWC2, (2011).

We discuss the nonlinear capacity limits imposed by inter-channel nonlinearities and signal-noise interaction, and investigate their impacts on the performance of coherent-detection based optical systems using high-level formats and electronic dispersion or intra-channel nonlinearity compensation.

http://www.opticsinfobase.org/abstract.cfm?URI=SPPCom-2011-SPWC2

N. Mac Suibhne, R. Watts, S. Sygletos, F. Garcia Gunning, L. Grüner-Nielsen, A.D. Ellis

OECC 2012, paper SC3_1043, (2012).

We experimentally demonstrate adiabatic soliton propagation in the fundamental mode of a few mode optical fibre and more complex behaviour in a higher order mode, indicating that the impact of nonlinearities differs for each mode.

http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6276540

Enhancing optical communications with brand new fibers

T.Morioka, Y.Awaji, R.Ryf, P.Winzer, D.J.Richardson, F.Poletti

IEEE Communications Magazine 2012 Vol.50(2) pp.s31-s42

Optical fibers have often been considered to offer effectively infinite capacity to support the rapid traffic growth essential to our information society. However, as demand has grown and technology has developed, we have begun to realize that there is a fundamental limit to fiber capacity of ~ 100 Tb/s per fiber for systems based on conventional single-core single-mode optical fiber as the transmission medium. This limit arises from the interplay of a number of factors including the Shannon limit, optical fiber nonlinearities, the fiber fuse effect, as well as optical amplifier bandwidth. This article reviews the most recent research efforts around the globe launched over the past few years with a view to overcome these limitations and substantially increase capacity by exploring the last degree of freedom available: the spatial domain. Central to this effort has been the development of brand new fibers for space-division multiplexing and mode-division multiplexing.

http://dx.doi.org/10.1109/MCOM.2012.6146483

Implementation of Tbit/s Networks

A.D.Ellis, F.C.G.Gunning

IEEE Photonics Conference 2011, Special Symposium on Terabit Optical Ethernet, paper MW3, (2011)

In this paper we examine the practical implications of increasing optical interface capacities into the Terabit/s regime.

http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6110481

Capacity in Fibre Optic Communications: The Case for a Radically New Fibre

A.D.Ellis, D.Rafique, S.Sygletos

IEEE Photonics Conference 2011, paper TuN1 (2011).

In this paper we review the implications of the so called nonlinear Shannon limit.

http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6110547

Analysis of Light scattering from Surface Roughness in Hollow-core Photonic Bandgap Fibers

Eric Numkam Fokoua1, Francesco Poletti1, David Richardson1; 1Optoelectronics Research Centre, University of Southampton, United Kingdom.

ECOC 2012, paper Mo.2.F.3

We present a theoretical method that combines statistical information from surface roughness, mode field distribution and fibre geometry to accurately describe roughness scattering in hollow-core photonic bandgap fibres. The method predicts angular distributions of scattered power and attenuation values that agree well with experimental data.

Nonlinear Pulse Distortion in Few-Mode Fiber

N. Mac Suibhne, R. Watts, S. Sygletos, F. C Garcia Gunning, L. Grüner-Nielsen, A. D. Ellis

ECOC 2012, paper Th.2.F.5, (2012).

Nonlinear pulse propagation in a few mode fiber is experimentally investigated, by measuring temporal and phase responses of the output pulses by use of a frequency discriminator technique, showing that selfphase modulation, dispersion and linear mode-coupling are the dominant effects.

Analysis of light scattering from surface roughness in hollow-core photonic bandgap fibers

Eric Numkam Fokoua, Francesco Poletti, and David J. Richardson, Univ. Southampton

Optics Express, Vol. 20, Issue 19, pp. 20980-20991 (2012)

We present a theoretical method for analyzing radiation loss from surface roughness scattering in hollow-core photonic bandgap fibers (HC-PBGFs). We treat the scattering process as induced dipole radiation and combine statistical information about surface roughness, mode field distribution and fibre geometry to accurately describe the far-field scattering distribution and loss in fibers with an arbitrary cross-sectional distribution of air *holes of any shape. The predicted angular scattering distribution, total scattering loss and the loss wavelength dependence are all shown to agree well with reported experimental data. Our method yields a simpler result than that obtained by more complex approaches and is to the best of our knowledge the first successful attempt to accurately describe roughness scattering in HC-PBGFs.*

http://dx.doi.org/10.1364/OE.20.020980

Impact of Mode Coupling on the Mode Dependent Loss Tolerance in Few Mode Fiber Transmission

Adriana P. Lobato Polo, Filipe Ferreira, Maxim Kuschnerov, Dirk van den Borne, Sander Jansen, Bernhard Spinnler, Berthold Lankl

ECOC'12, paper Tu.1.C.3

In this work the impact of mode-dependent loss (MDL) from optical amplifiers in few-mode fibers with weak and strong mode coupling is analyzed. For a 409-Gbit/s 3MDM-DP-QPSK system it is shown that strong mode coupling reduces the impact of MDL in a similar manner polarization- dependent loss is reduced by polarization mode dispersion.

The Impact of Differential Mode Delay on Mode-Division Multiplexed Coherent Optical OFDM Transmission

Adriana P. Lobato Polo, Filipe Ferreira, Beril Inan, Maxim Kuschnerov, Dirk van den Borne, Sander L. Jansen, Bernhard Spinnler4, Berthold Lankl

OFC 2012, paper OTu2C.2.

We analyze two-mode transmission for 402-Gb/s 3MDMPM- QPSK-OFDM modulation and different DMD values. We show that only with low-DMD fiber it is possible to effectively equalize mode coupling and bridge long-haul transmission distances.

http://www.opticsinfobase.org/abstract.cfm?URI=OFC-2012-OTu2C.2

DSP Requirements for MIMO Spatial Multiplexed Receivers

B. Inan, S. L. Jansen, B. Spinnler, F. Ferreira, D. van den Borne, M. Kuschnerov, A. P. Lobato, S. Adhikari, V. Sleiffer, N. Hanik

SUM 2012 IEEE Photonics Society Summer Topical Meeting on Space Division Multiplexing for Optical Systems and Networks, paper MC4.4 (Invited)

OFDM requires the lowest equalizer complexity for crosstalk compensation in a mode-division-multiplexing receiver. For a 2000-km transmission distance and less than 10% OFDM- specific overhead, the modal dispersion must be below 6 ps/km for 10x10 MIMO.

http://dx.doi.org/10.1109/PHOSST.2012.6280726

DSP complexity of mode-division multiplexed receivers

Beril Inan, Bernhard Spinnler, Filipe Ferreira, Dirk van den Borne, Adriana Lobato, Susmita Adhikari, Vincent A. J. M. Sleiffer, Maxim Kuschnerov, Norbert Hanik, and Sander L. Jansen

Optics Express, Vol. 20, Issue 10, pp. 10859-10869 (2012)

The complexities of common equalizer schemes are analytically analyzed in this paper in terms of complex multiplications per bit. Based on this approach we compare the complexity of mode-division multiplexed digital signal processing algorithms with different numbers of multiplexed modes in terms of modal dispersion and distance. It is found that training symbol based equalizers have significantly lower complexity compared to blind approaches for long-haul transmission. Among the training symbol based schemes, OFDM requires the lowest complexity for crosstalk compensation in a mode-division multiplexed receiver. The main challenge for training symbol based schemes is the additional overhead required to compensate modal crosstalk, which increases the data rate. In order to achieve 2000 km transmission, the effective modal dispersion must therefore be below 6 ps/km when the OFDM specific overhead is limited to 10%. It is concluded that for few mode transmission systems the reduction of modal delay is crucial to enable long-haul performance.

http://dx.doi.org/10.1364/OE.20.010859

Equalizer complexity of mode-division multiplexed coherent receivers

Inan, B., Spinnler, B., van den Borne, D., Ferreira, F., Lobato, A., Adhikari, S., Sleiffer, V.A.J.M., Hanik, N., Jansen, S.L.

14th International Conference on Transparent Optical Networks (ICTON), 2-5 July 2012, pages 1 – 4

One of the possible solutions is to use space division multiplexing in order to overcome the capacity crunch. Few mode fibers (FMF) have attracted a lot of attention in the recent years, however still a lot of research is required to enable transmission over FMF. One of the problems with the realization of FMF transmission is that these fibers have a modal dispersion which results in high number of equalization taps which might make the FMFs

impractical. The complexities of common equalizer schemes are analyzed in this paper in terms of complex multiplications per bit. It is found that training symbol based equalizers have significantly lower complexity compared to blind approaches for long-haul transmission. Among the training symbol based schemes, OFDM requires the lowest complexity for crosstalk compensation in a mode-division multiplexed receiver. The main challenge for training symbol based approaches is the increased data rate due to extra overhead required for cyclic prefix and training symbols. In order to achieve 2000 km transmission, the modal dispersion must be below 6 ps/km when the OFDM specific overhead is limited to 10%. This shows that for few mode transmission systems the reduction of modal delay is essential to enable long-haul performance.

http://dx.doi.org/10.1109/ICTON.2012.6254445

Equalizer Complexity of Mode Division Multiplexed Coherent Receivers

Beril Inan, Bernhard Spinnler, Filipe Ferreira, Adriana P. Lobato Polo, Susmita Adhikari, Vincent Sleiffer, Dirk van den Borne, Norbert Hanik, Sander L. Jansen

OFC 2012, paper OW3D.4

We show that OFDM requires the lowest equalizer complexity for crosstalk compensation in a mode-division-multiplexing receiver. For a 2000-km transmission distance and less than 10% OFDMspecific overhead, the modal dispersion must be below 12 ps/km.

http://www.opticsinfobase.org/abstract.cfm?URI=OFC-2012-OW3D.4

Semi-analytical model for linear modal coupling in few-mode fiber transmission

F. Ferreira, P. Monteiro, H. Silva

14th International Conference on Transparent Optical Networks (ICTON), 2-5 July 2012, paper Th.A1.5

This paper proposes a method for the semi-analytical solution of the coupled linear differential equations that describe the linear modal coupling arising in few mode fibers (FMFs) due to waveguide imperfections. The semi-analytical solutions obtained can be used for the modification of the split step Fourier method to include the respective linear effects. Considering a fiber with six linearly polarized modes (or ten modes, taking into account the degenerate versions) the solutions obtained proved to be accurate when compared to the numerical solutions obtained through the Runge-Kutta-Fehlberg method.

http://dx.doi.org/10.1109/ICTON.2012.6254446

Crosstalk Optimization of Phase Masks for Mode Multiplexing in Few Mode Fibers,

Filipe Ferreira, Dirk van den Borne, Paulo Monteiro, Henrique Silva

OFC 2012, paper JW2A.37

We show the design optimization of phase masks for mode conversion and subsequent mode division multiplexing / de-multiplexing. We focus on optimization of mask resolution and offset tolerance to minimize mode power crosstalk.

http://www.opticsinfobase.org/abstract.cfm?URI=NFOEC-2012-JW2A.37

Nonlinear Semi-Analytical Model for Simulation of Few-Mode Fiber Transmission

Filipe Ferreira, Student Member, IEEE, Sander Jansen, Senior Member, IEEE, Paulo Monteiro, Member, IEEE, and Henrique Silva, Member, IEEE

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 24, NO. 4, FEBRUARY 15, 2012, pp 240-242.

In this letter, a nonlinear semi-analytical model (NSAM) for simulation of few-mode fiber transmission is proposed. The NSAM considers the mode mixing arising from the Kerr effect and waveguide imperfections. An analytical explanation of the model is presented, as well as simulation results for the transmission over a two mode fiber (TMF) of 112 Gb/s using coherently detected polarization multiplexed quadrature phase-shift-keying modulation. The simulations show that by transmitting over only one of the two modes on TMFs, longhaul transmission can be realized without increase of receiver complexity. For a 6000-km transmission link, a small modal dispersion penalty is observed in the linear domain, while a significant increase of the nonlinear threshold is observed due to the large core of TMF.

http://dx.doi.org/10.1109/LPT.2011.2177250