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研究課題名（和文）Nonlinear transmission effects in few-mode optical fiber transmission systems

研究課題名（英文）Nonlinear transmission effects in few-mode optical fiber transmission systems

研究代表者

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研究成果の概要（和文）：多モードファイバーの異なるファイバーモードで伝播する信号間の非線形信号相互作用を、実験的に調査した。 我々は、モード内およびモード間非線形信号相互作用の相対強度を調査し、それが同様の強度である可能性があると結論付けた。 また、この実験結果を、モード間非線形信号相互作用の分析調査と比較し、良好に一致した。 さらに、予備の高非線形多モードファイバーを開発製造した。 このファイバーを使用して、1つのファイバーモードのCバンドから他のファイバーモードのLバンドへのさまざまな信号の変換が最小限の変換ペナルティとなることを示した。

研究成果の学術的意義や社会的意義
Optical fiber transmission systems form the backbone of the global communications infrastructure. The research results from this project allow to estimate the performance limitation of novel few-mode fibers for future-proof optical transmission systems.

研究成果の概要（英文）：Nonlinear signal interaction between signals that propagate in different fiber modes of a few-mode fiber have been investigated experimentally. we investigated the relative strength of intra- and intermodal nonlinear signal interactions, and concluded that it can be of similar strength. The results were published at ECOC2018. We further compared the experimental results with an analytical investigation of the intermodal nonlinear signal interaction, with good agreement. These results were published in the Journal of Lightwave Technology. We further developed and fabricated a preliminary highly nonlinear few-mode fiber. This fiber was used to demonstrate the conversion of various signals from the C Band in one fiber mode to the L Band in the other fiber mode with minimum conversion penalty. We published the results at OFC2019 where it was a top-scored paper. We got invited to contribute an article on this topic for IEEE JSTQE was recently published.

研究分野：Optical communications engineering

キーワード：space-division multiplex　multi-mode fiber　nonlinear signal prop　optical wavel conversion

１．研究開始当初の背景

Optical fiber transmission systems form the backbone of the global communications infrastructure. Due to the ever-increasing demand for optical communications systems with annual growth dates of up to 60%, novel technologies need to be investigated to allow such large growth rates with acceptable cost and energy consumption. Space-Division Multiplexing (SDM) is a promising technology to increase the data rates of optical fiber transmission systems with novel transmission fibers. One fiber type for SDM is called few-mode fiber (FMF). In contrast to currently deployed single-mode optical fibers, FMF support the propagation of several transversal modes at the same optical carrier wavelength. In an ideal FMF model, such fiber modes can propagate without interfering with each other. However, in an experimental implementation and especially in a product, the transversal fiber modes of FMF mix with each other. Such mixing can be separated into two fundamentally different mixing effects: linear and nonlinear mode mixing. Linear mode mixing can typically be inverted by usage of multiple-input / multiple-output (MIMO) equalization filters that are already well known from wireless communications. However, nonlinear signal mixing between fiber modes is a process that is difficult to reverse and is typically treated as an additional source of noise that ultimately limits the amount of data that can be transmitted in a fiber. However, in FMF, intermodal nonlinear signal mixing is a phenomenon that is much different from nonlinear signal interactions in traditional single-mode optical fibers, as due to so called phase-matching conditions, optical frequency components that are separated by large spectral gaps can have very strong interaction. This effect has been investigated theoretically before, but experimental evidence of the consequences of such intermodal nonlinear signal interactions were yet not known.

On the other hand, intermodal nonlinear signal interactions can be beneficial, if they can be exploited for nonlinear signal processing. Such signal processing has already been intensively investigated in single-mode fibers and is an interesting candidate technology for low energy-consumption, signal processing functionality such as wavelength conversion. Intermodal nonlinear signal processing is a completely new field of study.

２．研究の目的

The purpose of this study was two-fold:

1) To generate a better understanding of intermodal nonlinear signal interactions, being fundamental limitations to optical fiber transmission systems that use few-mode fibers. Such an understanding is a fundamental requirement to estimate the limitations of few-mode fibers in future optical fiber transmission systems

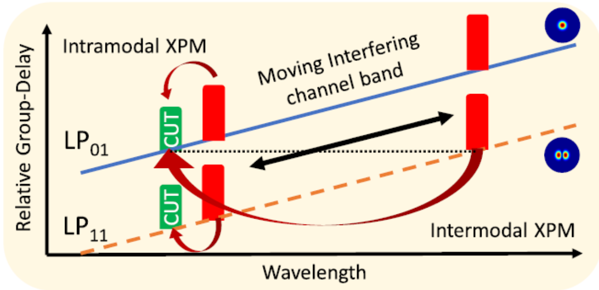
2) Investigation of intermodal nonlinear signal interactions for all-optical signal processing is a very attractive candidate technology for low power, all-optical signal processing functionality that can be applied e.g. in routing or switching of all optical signals, but also to open up new bandwidths in the optical spectrum that can be used for transmission of data but where transceiver and amplifier technology may not be available.

３．研究の方法

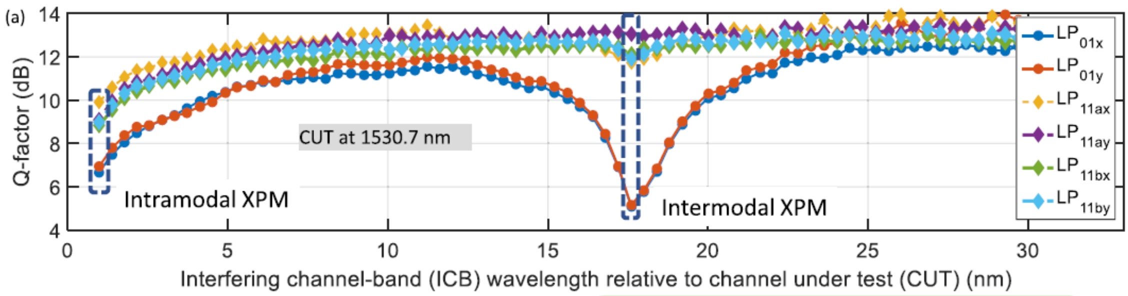
The method used to study the described phenomena in optical few-mode fibers were based on experimental investigations. For the first part, we built an optical few-mode fiber transmission experiment, where several wavelength channel can be generated, transmitted and received over a single few-mode fiber. Such transmission system was built for a single span of fiber with up to 36 km length but also in a so-called recirculating loop experiment, where the same fiber can be used multiple times in series for transmission, with distances of many hundred km. We have swept the wavelength of an interfering channel band to increase or reduce the strength of intermodal nonlinear signal distortions as well as to show the relative strength of intermodal and intramodal nonlinear signal distortions.

We further studied intermodal wavelength conversion with highly spectral efficient modulation formats from wavelengths within the C-band to wavelength channels within the L band. We have analyzed the signal degradation of the converted signals.

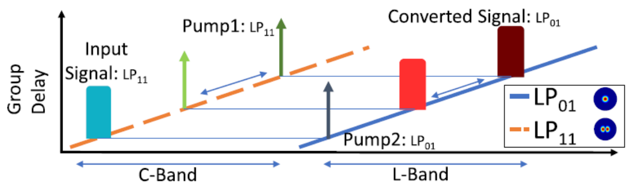
4．研究成果



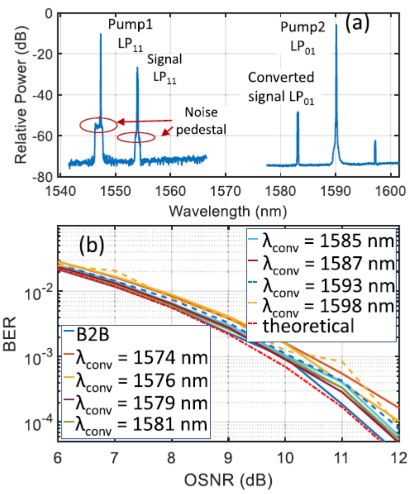
The figure on the right side shows the schematic of the implemented transmission experiment. A channel under test (CUT) was transmitted at one wavelength channel, with an interference channel band (ICB), who's wavelength was stepped through the entire C-band. For each wavelength position of the interfering channel band, the signal quality of the CUT was measured. The signal quality of the CUT can be expressed through Q-Factor. A high Q-Factor corresponds to a high quality of the signal. The figure below shows the Q-Factor of the CUT as a function of the wavelength separation between the CUT and the ICB. When the channels are in close proximity (left area of the plot), strong intramodal nonlinear signal distortion reduces



the signal quality. When increasing the distance between CUT and ICB, the Q-Factor increases, as the phase matching between interfering channels is weaker. At approximately 17 nm separation between CUT and ICB, strong intermodal nonlinear signal interactions degrade the signal in only two of the transversal modes of the transmission systems, where phase matching is very strong, accordingly to the schematic description above. Such intermodal nonlinear signal interactions have similar negative effects on the signal quality as intramodal nonlinear signal interactions and hence need to be considered when designing future transmission systems with few-mode fibers.



Investigation of intermodal nonlinear all optical wavelength conversion is schematically shown on the left. An input signal was launched into the C-band of one fiber mode of a highly nonlinear few-mode fiber. Two pump waves at different wavelengths were each launched into a different fiber mode. Due to intermodal nonlinear signal interactions, a copy of the signal is generated in the fiber mode where it was not launched into. The target wavelength of this wavelength conversion process can be freely chosen by tuning the wavelength of Pump1 accordingly. The top figure on the right shows actual measured optical spectra of input signal, pumps and the converted signal. The lower figure on the right shows the bit-error rate (BER) of the original signal and the converted signals at various target wavelengths as a function of the optical signal to noise ratio (OSNR). The OSNR penalty is less than 1 dB for all analyzed target wavelengths, indicating very low signal quality penalty from the conversion process.



５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　0件）

１．著者名 G. Rademacher, R.S. Luis, B.J. Puttnam, R. Maruyama, K. Aikawa, Y. Awaji, H. Furukawa, K. Petermann, N. Wada	４．巻 37
２．論文標題 Investigation of Intermodal Nonlinear Signal Distortions in Few-Mode Fiber Transmission	５．発行年 2019年
３．雑誌名 IEEE/OSA Journal of Lightwave Technology	６．最初と最後の頁 1273 - 1279
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/JLT.2019.2892052	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 G. Rademacher, R.S. Luis, B.J. Puttnam, H. Furukawa, R. Maruyama, K. Aikawa, Y. Awaji, N. Wada	４．巻 30
２．論文標題 Investigation of Intermodal Four-Wave Mixing for Nonlinear Signal Processing in Few-Mode Fibers	５．発行年 2018年
３．雑誌名 IEEE Photonics Technology Letters	６．最初と最後の頁 1527 - 1530
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LPT.2018.2856755	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 G. Rademacher, R.S. Luis, B.J. Puttnam, Y. Awaji, M. Suzuki, T. Hasegawa, N. Wada	４．巻 26
２．論文標題 Wideband Intermodal Nonlinear Signal Processing With a Highly Nonlinear Few-Mode Fiber	５．発行年 2020年
３．雑誌名 IEEE Journal of Selected Topics in Quantum Electronics	６．最初と最後の頁 1-7
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/JSTQE.2020.2984563	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計5件（うち招待講演　3件／うち国際学会　3件）

１．発表者名 G. Rademacher, R.S. Luis, B.J. Puttnam, T.A. Eriksson, H. Furukawa, Y. Awaji, R. Maruyama, K. Aikawa, N. Wada
２．発表標題 Mode and Wavelength Conversion in Few-Mode Fibers
３．学会等名 EXAT February Technical Meeting（招待講演）（国際学会）
４．発表年 2019年

1．発表者名 G. Rademacher, R.S. Luis, B.J. Puttnam, Y. Awaji, M. Suzuki, T. Hasegawa, N. Wada
2．発表標題 Wide-Band Intermodal Wavelength Conversion in a Dispersion Engineered Highly Nonlinear FMF
3．学会等名 Optical Fiber Communication Conference (OFC)（国際学会）
4．発表年 2019年

1．発表者名 G. Rademacher, R.S. Luis, B.J. Puttnam, H. Furukawa, R. Maruyama, K. Aikawa, Y. Awaji, N. Wada
2．発表標題 Experimental Investigation of Intermodal Nonlinear Signal Degradation in a Few-Mode Fiber Transmission System
3．学会等名 European Conference on Optical Communication (ECOC)（国際学会）
4．発表年 2018年

1．発表者名 G. Rademacher, R.S. Luis, B.J. Puttnam, H. Furukawa, R. Maruyama, K. Aikawa, Y. Awaji, N. Wada
2．発表標題 Experimental Investigation of Intermodal Nonlinear Signal Degradation in a Few-Mode Fiber Transmission System
3．学会等名 2018 Munich Workshop on Information Theory of Optical Fiber（招待講演）
4．発表年 2018年

1．発表者名 G. Rademacher, R.S. Luis, B.J. Puttnam, Y. Awaji, N. Wada, H. Furukawa
2．発表標題 Technologies for High Capacity SDM Transmission Systems
3．学会等名 NICT - SPOC workshop（招待講演）
4．発表年 2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

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