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Polarization-Insensitive 640 Gb/s Demultiplexing Based on Four Wave Mixing in a Polarization-Maintaining Fibre Loop

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Abstract—**Polarization-insensitive 640 Gbit/s demultiplexing for OTDM data signals is demonstrated using a 100 m polarization-maintaining highly non-linear fibre. The scheme is based on four wave mixing (FWM) in a polarization-maintaining fibre loop (PMFL) with bidirectional operation. Less than 0.2 dB polarization dependence is obtained. The FWM efficiency is about −6 dB if the passive loss of the PMFL is not included. The flatness characteristic of the FWM efficiencies allows for the OTDM demultiplexing of a high speed signal with a bandwidth of 1.2 THz. Error free performance with low penalty for the demultiplexed 10 Gbit/s signal is achieved for the polarization scrambled 640 Gbit/s data signal. BER measurements and eye-diagrams show that the demultiplexed 10 Gbit/s signals with and without polarization scrambling have almost identical performance.**

Index Terms—**Demultiplexing, four wave mixing, optical time division multiplexing (OTDM), polarization insensitive, polarization-maintaining highly non-linear fibre.**

I. INTRODUCTION

SWITCHING is a key functionality in digital communication systems, and can enable e.g., demultiplexing and routing. High-speed demultiplexing is an important element in ultra-fast serial optical communication systems based on time division multiplexing (TDM). [1], [2]. A high-speed TDM signal can be demultiplexed to low-speed signals by electrical TDM (ETDM) and optical TDM (OTDM). Currently, 107 Gb/s demultiplexing based on an integrated ETDM receiver is the state-of-the-art [3]–[5]. However, it will be very difficult to realize the ETDM demultiplexing above 160 Gb/s in the near future. In contrast, 640 Gb/s OTDM demultiplexing was already realized in 1998. [6]. With the same baud rate, polarization multiplexing and advanced modulation formats were used to further increase the data bit rate to 1.28 Tb/s, 2.56 Tb/s and 3.6 Tb/s [7]–[9]. The highest symbol rate of OTDM

demultiplexing to date is 1.28 Tbaud and using an advanced modulation format this has recently been employed to generate a 5.1 Tb/s data signal [10], [11].

Among the techniques for OTDM demultiplexing, those based on cross phase modulation (XPM) and four wave mixing (FWM) are attractive due to their fast response and possiblility to preserve phase information. Several schemes have been demonstrated for OTDM demultiplexing at 640 Gb/s or above, such as a non-linear optical loop mirror (NOLM) [6]–[8], [10], FWM in a fibre or a chalcogenide waveguide [12], [13], XPM and subsequent filtering in a semiconductor optical amplifier (SOA). [14], and a digital coherent receiver with an OTDM demultiplexing function [15], [9].

Polarization insensitivity is also highly advantageous for demultiplexing in practice. A polarization insensitive optical switch can process an incoming data signal with an arbitrary state of polarization (SOP) and alleviate the necessity of tracking and locking the input SOP to a desired SOP before the switch. A polarization insensitive switch based on XPM is achieved by twisting a non-PM fibre into a so called circular-birefringence fibre (CBF), since equal nonlinear phase-shifts for the parallel and the orthogonal polarization can be obtained [16]–[19]. Another elegant method exploits a special property of XPM induced phase-shifts [20], [21]. Besides, a number of polarization diversity schemes were proposed and demonstrated, such as a polarization diversity loop with bidirectional operation [22]–[24], temporally separating two orthogonal SOP components by introducing a delay between them before the non-linear medium [25]–[27], and using copolarized-pump or orthogonal-pump FWM [28], [29].

In this paper, polarization insensitive 640 Gbit/s demultiplexing is demonstrated for OTDM data signals using a 100 m long polarization-maintaining highly non-linear fibre (PM-HNLF). The basic principle is based on FWM in a polarization-maintaining fibre loop with bidirectional operation in a polarization diversity scheme. Error free performance with low penalty is achieved with less than 0.2 dB polarization dependence of the FWM efficiency. This paper elaborates on the results in [12] and provides more detailed characterizations and explanations. Section II explains the operation principle of the polarization insensitive optical switch. Section III shows the characteristics of the optical switch, including the FWM conversion bandwidth and the switching window for the OTDM demultiplexing. In Section IV, we describe the polarization insensitive 640 Gbit/s demultiplexing experiment in detail. Finally, Section V summarizes the results.
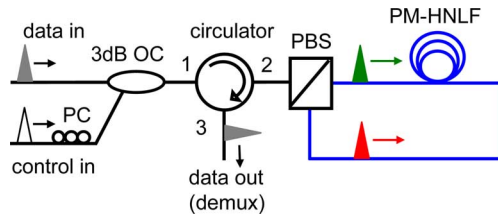
Fig. 1. Polarization insensitive optical switch using a polarization maintaining highly non-linear fibre (PM-HNLF) loop with bidirectional operation. (Blue lines indicate polarization maintaining fibres.).
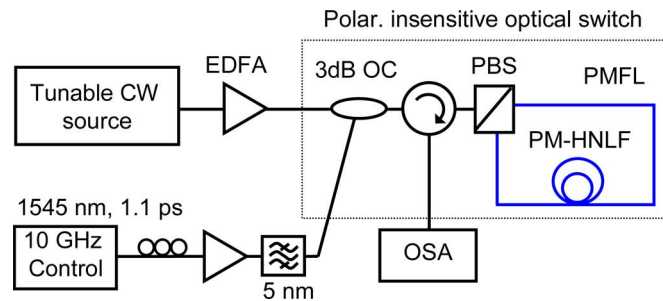

Fig. 2. Measurement setup of the polarization insensitive optical switch.

II. OPERATION PRINCIPLE

The operation principle of the polarization maintaining highly non-linear fibre loop (PMFL) is shown in Fig. 1. A data signal and a control pulse are launched together into a polarization beam splitter (PBS) through a 3-dB optical coupler (OC) and a circulator. In the PMFL switch, the data signal is split into two polarization components that propagate through the fibre loop with opposite directions. The fast axis of the PBS is rotated by 90° inside; therefore, both outputs of the PBS are slow axis and aligned with the slow axis of the PM-HNLF. All signals always propagate along the slow axis in the fibre loop. If the control pulse is launched into the PBS with 45° polarization, achieving equal intensity in both directions of the loop, the FWM conversion efficiencies (proportional to the square of the pump intensity) of both directions will be kept constant. When the polarization of the incoming data signal is scrambled, the power distribution of the data signal at the PBS outputs is changed but the total power of the FWM products will be kept constant. The FWM products are recombined in the PBS and output from port 3 of the circulator. The principle of the PMFL is similar to the polarization diversity scheme presented in [24], [30].

III. CHARACTERISTICS OF THE OPTICAL SWITCH

We first investigated the wavelength dependence of the FWM conversion efficiency to determine the FWM bandwidth. The measurement setup is shown in Fig. 2. The 10 GHz control pulse at 1545 nm is generated by an Erbium Glass Oscillator (ERGO) pulse source and further compressed to a 1.1 ps pulse in a 400 m dispersion flattened highly non-linear fibre (DF-HNLF). The control pulse is amplified by an erbium-doped fibre amplifier (EDFA), filtered by a 5 nm optical bandpass filter (OBF), and then launched into the polarization insensitive optical switch. The tuneable continuous wave (CW) source serves as data signal
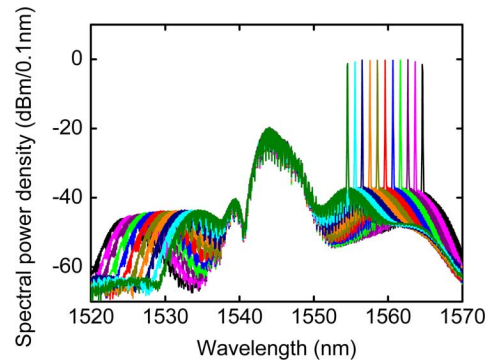
Fig. 3. FWM spectra for different input CW wavelengths.
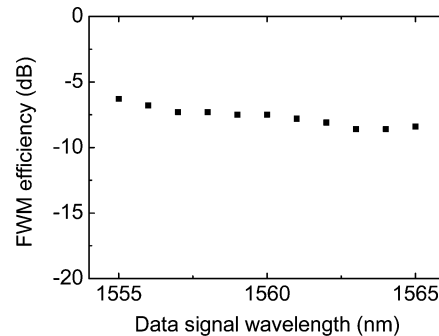
Fig. 4. FWM efficiencies versus different input data signal wavelengths.

Fig. 5. Calculated GVD walk-off (dash) and switching window (solid) for the control pulse at 1545 nm and the data signal at different wavelengths.

here and the wavelength is tuned from 1555 nm to 1565 nm. The optical spectra after the FWM are measured by an optical spectrum analyser (OSA), which is shown in Fig. 3. The FWM efficiency is derived from the spectra by integrating the power of the FWM products, and taking into account that the control pulses only appear for 1.1 ps in every period (100 ps at the 10 GHz repetition rate) and hence only about 1.1 % of the CW signal takes part in the FWM process (assuming the control pulses have a rectangular shape). Therefore, the FWM efficiency is obtained by comparing the integrated FWM product power to 1.1 % of the average CW power. As shown in Fig. 4, the FWM efficiencies are kept almost constant for the input signals from 1555 nm to 1565 nm and the fluctuations are only ~2 dB. The flatness characteristic of the FWM efficiencies allows for the OTDM demultiplexing of a high speed signal with a large bandwidth (> 1.2 THz).
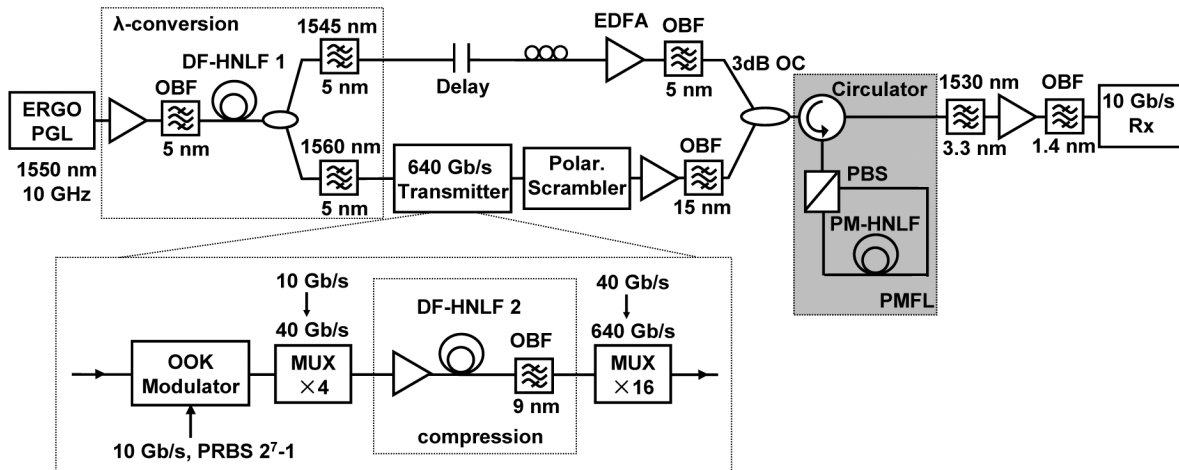
Fig. 6. Experimental setup for the polarization-insensitive 640 Gbit/s OTDM demultiplexing.

The 100 m PM-HNLF (provided by OFS Fitel Denmark Aps) has zero dispersion at 1545 nm and a dispersion slope of 0.025 ps/nm^2 km. Since the control wavelength is set at the zero-dispersion wavelength, for signal wavelengths far away from the control, the switching window will be broadened due to the walk-off between the control pulse and the data pulse due to the group velocity delay (GVD). The switching window depends on both the walk-off and the FWHM of the control pulse. Since the intensity of the FWM product is proportional to the square of the pump intensity, the switching window is the FWHM of the square of the control pulse if the walk-off is zero. Fig. 5 shows th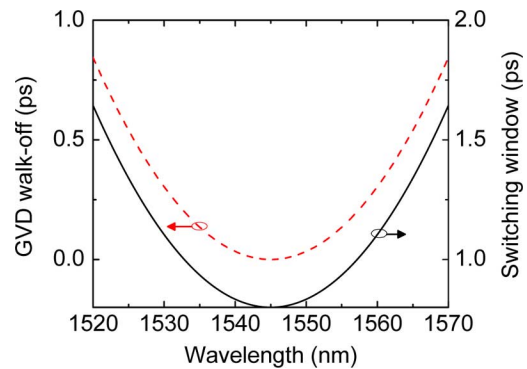e calculated GVD walk-off and switching window for the control pulse at 1545 nm and the data signal at different wavelengths. For a signal wavelength at 1560 nm, the walk-off is about 300 fs and the switching window is about 1.1 ps. Actually, the small amount of walk-off results in a more flat switching window and is helpful to increase the tolerance to timing jitter.

IV. 640 GBIT/S DEMULTIPLEXING EXPERIMENT

A. Experimental Setup

The experimental setup for the polarization-insensitive 640 Gbit/s OTDM demultiplexing is shown in Fig. 6. It includes a 640 Gbit/s OTDM transmitter, a 10 GHz control pulse generator and the polarization-insensitive 640 Gbit/s OTDM demultiplexer. The erbium glass oscillating pulse-generating laser (ERGO-PGL) produces 10 GHz pulses at 1550 nm with a 1.5 ps full-width at half-maximum (FWHM). The 10 GHz pulses are amplified to an average power of 27 dBm, filtered by a 5 nm optical bandpass filter (OBF) in order to suppress amplified spontaneous emission (ASE) noises, and finally launched into a HNLF. The spectrum of these pulses is broadened in the 400 m dispersion-flattened highly non-linear fibre (DF-HNLF 1, dispersion D = -0.45 ps/nm/km and dispersion slope S = 0.006 ps/nm^2/km at 1550 nm, nonlinear coefficient $\gamma = 10.5$ W^{-1} km^{-1}), due to self-phase modulation (SPM). The SPM effect results in a ~50 nm spectrum, which is filtered at 1545 nm using a 5 nm OBF to obtain the 10 GHz control pulses and is also filtered at 1560 nm with another 5 nm OBF to generate the 10 GHz pulses for the data signal. The 10 GHz pulses at 1560 nm

are encoded by on-off keying (OOK) with a 10 Gbit/s PRBS $(2^7 - 1)$ signal in a Mach–Zehnder modulator. The modulated 10 Gbit/s OOK signal is multiplexed in time to 40 Gbit/s using a passive fibre-delay multiplexer (MUX × 4). The 40 Gbit/s data pulses are further compressed in a 100 m DF-HNLF 2 (D = -1.07 ps/nm/km and S = 0.004 ps/nm^2/km at 1560 nm, $\gamma = 10.5$ W^{-1} km^{-1}). The average input power of the 40 GHz pulses into DF-HNLF 2 is 25 dBm. The SPM process in the DF-HNLFs results in an up-chirped output pulse that can be compressed by an element with positive dispersion (standard SMF is used in the experiment). After the compression, the 40 Gbit/s PRBS signal is then multiplexed in time to 640 Gbit/s using another multiplexer (MUX × 16). The multiplexers used in the experiment are PRBS $(2^7 - 1)$ maintaining and polarization maintaining. An eye diagram of the 640 Gbit/s data signal, obtained with an optical sampling oscilloscope, is shown in Fig. 7(a). As shown in Fig. 7(b), the FWHM of the data and control pulses are 650 fs and 1.1 ps, respectively.

The polarization-insensitive 640 Gbit/s demultiplexer mainly consists of the polarization-maintaining highly non-linear fibre loop (PMFL) and a filtering subsystem. The PMFL includes a circulator, a polarization beam splitter and a 100 m PM-HNLF (zero dispersion at 1545 nm and a dispersion slope of 0.025 ps/nm^2 km). The PM-HNLF has several advantages over a non-PM-HNLF, such as stable operation over a long time, eliminating the polarization changes due to polarization mode dispersion (PMD) which can otherwise severely limit the working bandwidth of effective FWM conversion in the fibre.

The total passive loss of the PMFL is 4.5 dB. The output filtering subsystem includes a 3.3 nm OBF, a 1.4 nm filter and an EDFA in between. The input 640 Gbit/s data signal is amplified by an EDFA, filtered by a 15 nm OBF, and then launched into the PMFL through a 3 dB coupler. The data signal power is 17.1 dBm at the input of the circulator. The polarization of the data signal is scrambled with a polarization scrambler (FiberPro-PS-155-A) in order to test the polarization insensitivity. The control pulses at 1545 nm are amplified, filtered by a 5 nm filter and also launched into the PMFL. The control power is 14.6 dBm at the input of the circulator. The polarization of the control pulses is adjusted for an equal power splitting at the PBS outputs. At the
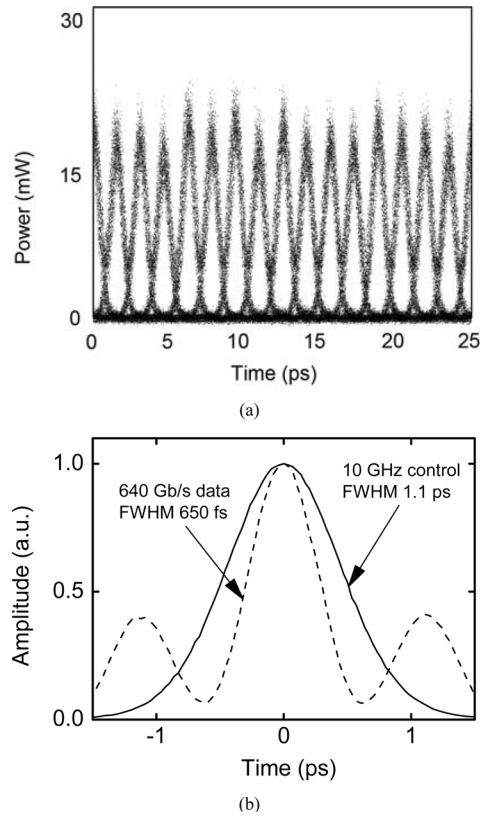
Fig. 7. (a) Eye diagram of the 640 Gbit/s OTDM data signal; (b) autocorrelations of data (dash) and control pulses (solid).
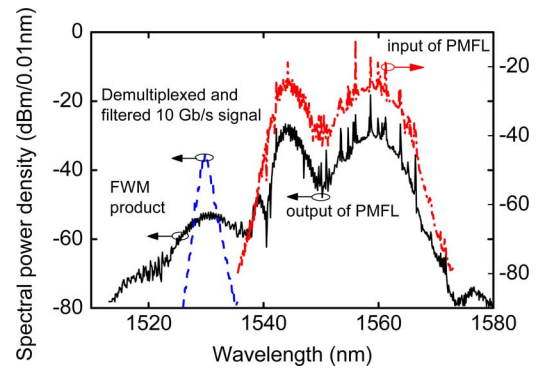

Fig. 8. Spectra at the input (dash dotted) and output (solid) of the PMFL, and demultiplexed and filtered 10 Gb/s signal (dashed).

Fig. 9. (a) Eye diagrams of the demultiplexed signal with and without polarization scrambling; (b) power fluctuations of the demultiplexed signal with polarization scrambling.

output of the circulator, the signals are launched into the filtering subsystem to separate the FWM product from the residual original data and control signal. Finally, the demultiplexed 10 Gbit/s signal is detected by a 10 Gbit/s receiver.

B. Experimental Results

The spectrum at the input (dotted line) and the output (solid line) of the PMFL is shown in Fig. 8. If the passive loss of the PMFL is not included, the FWM conversion efficiency is about −6 dB, taking into account that only one of 64 OTDM tributaries takes part in the FWM process. The FWM product is extracted by optical filtering and amplification to allow for the detection of the demultiplexed channel, which is also shown in Fig. 8 (dashed line). The control pulses are well suppressed by the cascaded filters. A 27 dB spectral contrast is obtained between the demultiplexed signal and the residual control pulses by measuring the power at the wavelength of FWM product (1530 nm) when original data signal is switched on or off.

To characterise the residual polarization sensitivity of the demultiplexer, the power fluctuation of the demultiplexed signal versus time is measured, with a ∼113 kHz polarization scrambling. The maximum fluctuation is less than 0.2 dB, making the scrambling period only barely discernible, as shown in Fig. 9(b). The eye diagrams of the demultiplexed 10 Gbit/s from the 640 Gbit/s data signal with and without polarization scrambling are shown in Fig. 9(a). The eye diagrams show negligible difference irrespective of whether the scrambler is on or off.

To further characterise the performance of the polarization-insensitive 640 Gbit/s OTDM demultiplexer, bit error rate (BER) measurements were carried out as a function of received power for the 10 Gbit/s signal back-to-back (B2B), and the demultiplexed 10 Gbit/s signal from the 640 Gbit/s data signal with and without polarization scrambling, as shown in Fig. 10. Error-free demultiplexing is achieved for the polarization scrambled 640 Gbit/s data signal. The BER curves of the B2B signal and demultiplexed signal show different slopes, mainly because of the pulse compression part in the OTDM transmitter and the wavelength difference between the demultiplexed signal (1530 nm) and B2B signal (1560 nm). Therefore, the demultiplexed 10 Gbit/s signal has not a constant penalty compared to the 10 Gbit/s signal back-to-back. However, the results indicate that the additional penalty caused by the polarization scrambling is almost negligible. The difference in the receiver sensitivity for a BER of 10^{-9} between scrambling on and off is 0.4 dB. The measurements shown in Fig. 10 are made for a single tributary. The inset shows the receiver sensitivity at BER

Fig. 10. BER performance of the demultiplexed 640 Gbit/s OTDM data with and without polarization scrambling.

of 10^{-9} for five adjacent tributaries. Error free operations are achieved for all five tributaries with a spread of $\sim$5 dB.
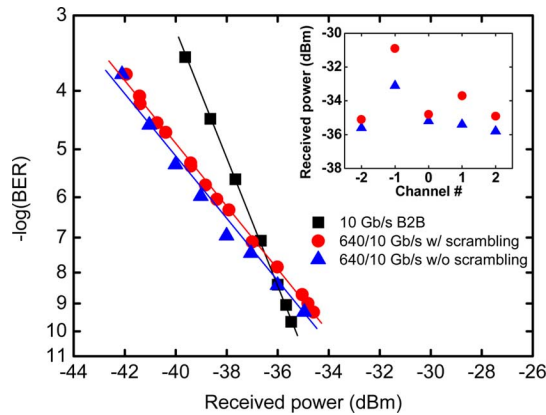
V. CONCLUSION

We have demonstrated polarization insensitive 640 Gbit/s demultiplexing of OTDM data signals based on FWM in a polarization-maintaining fibre loop. Less than 0.2 dB polarization dependence is obtained. We also investigated the characteristics of the polarization insensitive optical switch. The FWM efficiency is about -6 dB if the passive loss of the PMFL is not included. In addition, the FWM efficiency shows a flat characteristic for the input signals from 1555 nm to 1565 nm, which allows for the OTDM demultiplexing of a high speed signal with a bandwidth of 1.2 THz. Error free performance with low penalty for the demultiplexed 10 Gbit/s signal is achieved for the polarization scrambled 640 Gbit/s data signal.

ACKNOWLEDGMENT

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Denmark and Tellabs Denmark. From 1995 to 1998, he coordinated the participation of Technical University of Denmark in the EU ACTS project METON (METropolitan Optical Network) and he followed his co-workers contributions to the four EU IST projects METEOR (MEtropolitan TErabit Optical Ring), STOLAS (Switching Technologies for Optically Labeled Signals), TOPRATE (Terabit/s Optical Transmission Systems based on UltraHigh Channel Bitrate) and LASAGNE (All-optical Label Swapping Employing Optical Logic Gates in Network Nodes). Since 1998, he has been Professor in optical communications at DTU Fotonik. He has been Chairman of the Danish Defense Research Council, member of NATO Research and Technology Board and NATO Science Committee. He has also been a member of the Danish Technical Research Council, the boards of TERMA Elektronik, Kryolitselskabet Øresund, Telecom Danmark and DELTA (Danish Electronics, Light & Acoustics) and the Scientific Council for the Danish National Encyclopedia. He has served many times at the technical program committees for the American conferences Optical Fiber Communication Conference (OFC) and Conference on Lasers and Electro-Optics (CLEO) and for the European Conference on Optical Communication (ECOC). He was Conference Chairman for ECOC 1981 and again for ECOC 2002, both in Copenhagen. He has also been a member of the Scientific Advisory Board for Virtual Photonics Incorporated (VPI) 1997–2002. He has been Chairman of the peer review panel PE7 Systems and Communication Engineering under the European Research Council since 2009, and has been a member of the Danish Academy of Technical Sciences since 1978. His current research interests are optical signal processing, optical multi-level modulation formats and 640–5000 Gbit/s optical communication. He has educated more than 80 Ph.D.s. He has also been a member of numerous evaluation committees at Technical University of Denmark and in other countries - in 2002, 2007 and 2008 Stiftelsen för Strategisk Forskning, in 2003 and 2004 Vetenskapsrâdet and Chalmers Tekniska Högskolan in Sweden.

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