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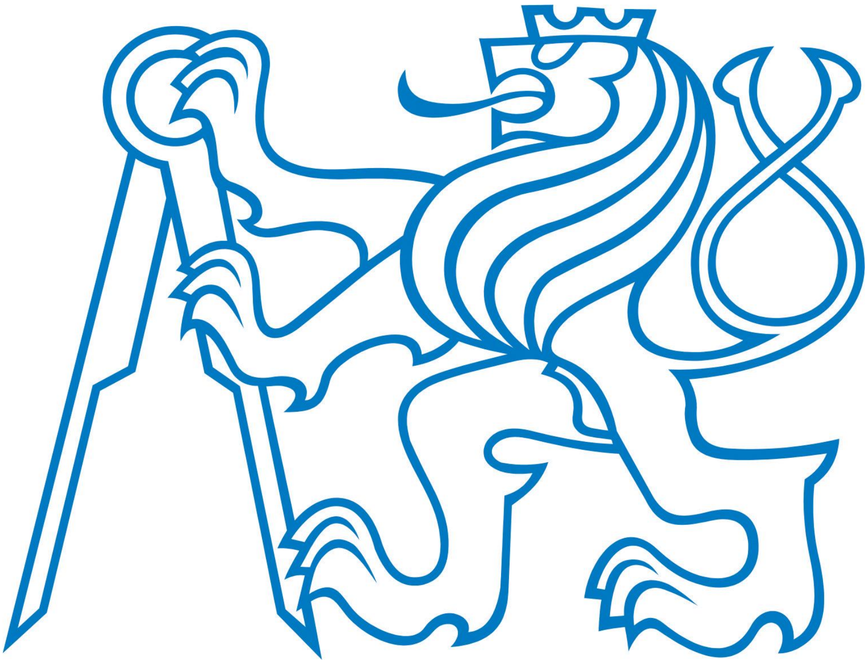

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Electromagnetic Field

Ing. Matěj Komanec

OPTICAL PACKET SWITCHING TECHNIQUES BASED ON NONLINEAR OPTICS

Ph.D. Programme:

Electrical Engineering and Information Technology

Branch of study: Radioelectronics

Doctoral thesis statement for obtaining the academic title
of ”Doctor”, abbreviated to ”Ph.D.”

Prague, August 2013

The doctoral thesis was produced in full-time manner Ph.D. study at the department of electromagnetic field of the Faculty of Electrical Engineering of the CTU in Prague

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CURRENT SITUATION OF THE STUDIED PROBLEM

Data transmission over a single optical fiber has recently exceeded 100 Tbps [1]. The growth of data traffic naturally imposes demands for an all-optical network solutions, such as optical burst switching or optical packet switching. All-optical switching, more specifically optical packet switching (OPS) provides an opportunity to switch data traffic in an optical manner excluding all or most of opto-electronic conversion.

Another reason for all-optical solutions lies in newly applied spectrally efficient modulation formats in optical communication, e.g. differential phase shift keying (DPSK) [2] , differential quadrature phase shift keying (DQPSK) [3], multiple-quadrature amplitude modulation (m-QAM) [4] and novel multiplexing methods, e.g. orthogonal frequency division-multiplexing (OFDM) [5] and polarization division-multiplexing (PDM) [6].

Optical packet switch

General OPS description considers an optical packet composed of a label and data payload at the OPS input as depicted in Fig. 1. Label is separated from the payload and processed. For label filtering a wavelength-division demultiplexer, an arrayed-waveguide grating (AWG) or a spectrally-narrow fiber Bragg grating (FBG) accompanied by a circulator can be employed. For label processing two basic concepts are represented by an all-optical setup or an electro-optic hybrid setup. Hybrid OPS converts the label into an electrical representation and processes it in a CPU - generally a digital signal processor or a field-programmable gateway array - and then a routing signal is generated, according to the label content. Hybrid solution sustains the advantages of electronic processing and preserves the optical data payload format and bit rate. All-optical solution were proposed recently [7], with increasing label content and processing capabilities. According to label processing time, the payload is buffered for an appropriate time period. After the payload is switched to the proper output a new label is attached to the data payload, thus forming a new optical packet for further optical network transmission.

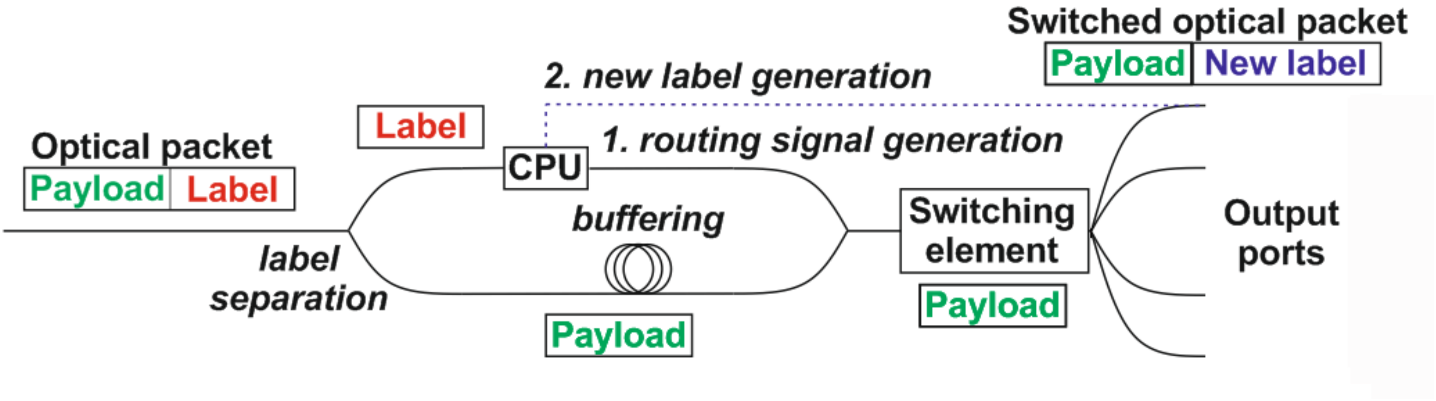

Figure 1: Generalized setup of OPS introducing main function blocs.

State-of-art labelling techniques include the serial labelling method [8], optical carrier suppression and separation [9], out-band labelling [10] and in-band labelling [7], where recently enhanced in-band RF-tone labelling was achieved [11].

Opto-electronic conversion and direct detection can be employed for label recognition only when the label is represented by the OOK or DPSK [12]. With the advent of novel modulation formats, higher bitrates and spectrally efficient data transfers, all-optical label processing became essential. Orthogonal label generation and recognition was presented in [13].

There are three major switching schemes, the broadcast-and-select switching technique [14], the space-switch [15] and the wavelength routing scheme [16].

The switching process is closely related to the utilized switching fabric. Planar switching fabrics are represented either by a monolithically integrated switch based on Indium Phosphide (InP) [17], a switch based on Perovskite Lead Lanthanum Zirconate Titanate (PLZT) [18] or a switch formed by micro-electro-mechanical systems (MEMS) [19]. Another approach is to utilize nonlinearities of the second or third order, such as cross-phase modulation (XPM), cross-gain modulation (XGM) or four-wave mixing (FWM) in semiconductor optical amplifiers or optical fibers.

Nonlinear fiber-based switches

Nonlinear fiber-based switches are either exploiting XPM in a NOLM configuration [20], or for spectral broadening [21], or together with employing fiber gratings [22]. FWM-based fiber switches are either in a one-pump [23] or two-pump [24] configuration, which is utilized for multicasting. Both switches can be enhanced by the Raman effect [25]. A significant drawback of nonlinear fiber-based switches is polarization sensitivity, whereas with unproper adjustment no XPM or FWM may occur and the optical packet will not be switched. Polarization insensitive setup was proposed in [26, 27] for HNLF and photonic crystal fiber (PCF) respectively (Fig. 2), where a polarization beam splitter (PBS) was employed to divide the signal and the pump into both polarization axes and then they co-propagated in a loop configuration, clockwise and counter-clockwise. The only requirement was that the pump is polarized 45° along the principal axis, so that the pump power is distributed evenly among both polarization axes. Polarization sensitivity of 0.2dB was achieved in [26].

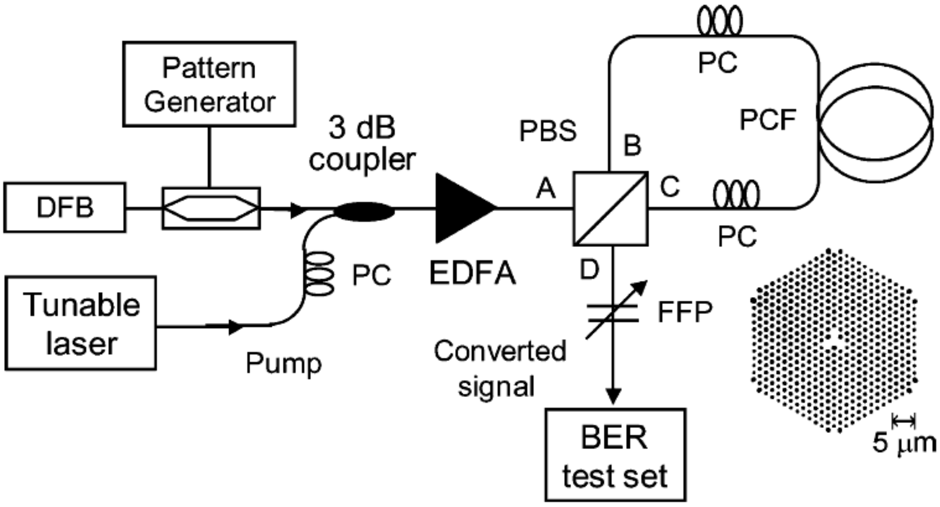

Figure 2: Polarization insensitive setup utilizing PBS in a nonlinear loop [26, 27].

Fibers with enhanced nonlinearity

For comparison of nonlinear fibers the nonlinear coefficient γ is utilized, defined as:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}, \tag{1}$$

where A_{eff} is the effective mode area, λ is wavelength and n_2 stands for the nonlinear refractive index of the fiber. Considering fixed wavelength (C-band wavelengths for optical communication) it is possible to achieve higher γ by reducing A_{eff}. This approach implies increased coupling losses and is limited by the employed wavelength. When the wavelength is close to or lower than the core diameter, light is no further guided by the total internal refraction. To increase n_2 it is necessary to change the glass composition as is summarized in Fig. 3.

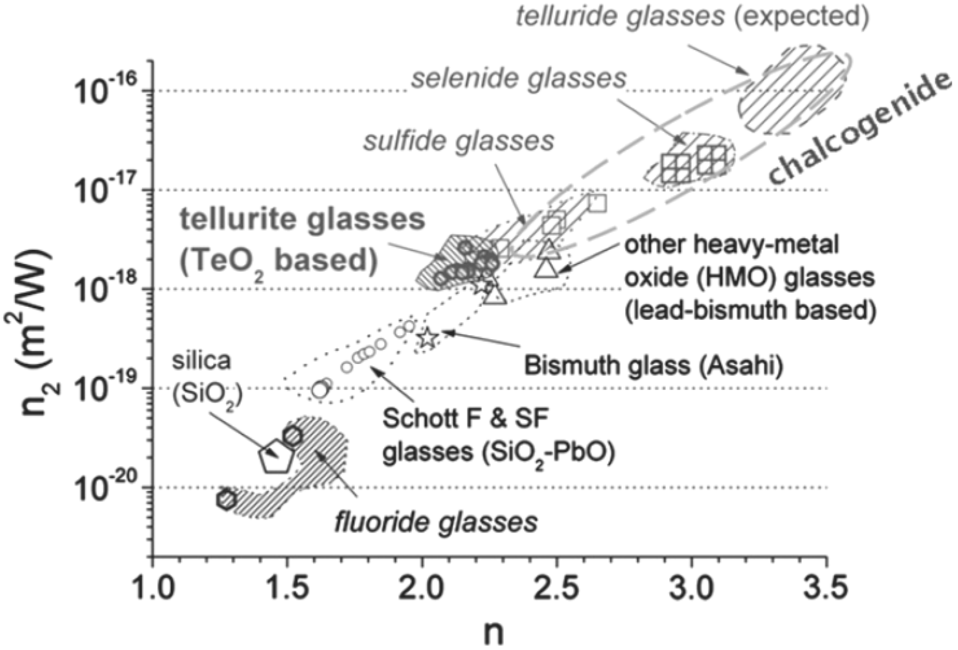

Figure 3: Dependence of the nonlinear refractive index on the refractive index for different glass materials [28].

Dispersion-shifted highly nonlinear optical fibre (DS-HNLF) is a special type of HNLF, with ZDWL in the vicinity of 1550nm. In 2006 γ of 30.0W^{-1}km^{-1} was reported [29] with further reduction of A_{eff} to 8.5μm^2.

Chalcogenide glass fibers (planar waveguides) provide extremely large nonlinearities (n_2 is 100 $\sim$ 1000 times greater than in silica) and high refractive indices (e.g. approximately 2.4 and 2.8 for arsenide-sulfide and arsenide-selenide respectively), which leads to suitable employment in high-power delivery for CO or CO_2 lasers [30], supercontinuum generation [31], utilizion in all-optical devices [32] , for extremely efficient four-wave mixing [33] and slow light applications [34].

Microstuctured fibers (MOFs) with only a few (<10) air holes are denominated as suspended core fibers (SCFs). In 2008 silica SCFs with increased nonlinearity were presented [35] achieved by extreme reduction of the core size. As the technology has matured, novel glass materials have been utilized for microstructured fiber designs. First report of a non-silica MOF came in year 2000 by T.M.Monro et al. [36]. Later chalcogenide photonic crystal fibers (CHG-PCFs) with As_2Se_3 composition was presented [37] obtaining γ of more than $2000W^{-1}km^{-1}$. The highest achieved nonlinearity γ of approximately $46000W^{-1}km^{-1}$ was presented [38].

Microstructured lead-bismuth-gallium (LBG) fibers stand for a comparative candidate to conventional chalcogenide fiber. Nonlinearity of more than $1000W^{-1}km^{-1}$ was measured at 1064nm [39] for LBG-PCF. Supercontinuum generation was presented on a 2cm and 8cm long LBG-PCF respetively [40]. In Fig. 4 cross-sections of LBG-SCF are presented. Core diameter was 1.09μm, the large airhole was $\sim 29.3\mu$m with thin bringes of $\sim 0.08\mu$m between the airholes. The fiber diamater was 107μm. Recent efforts were aimed at LBG-SCF production with core diameter under 1μm.

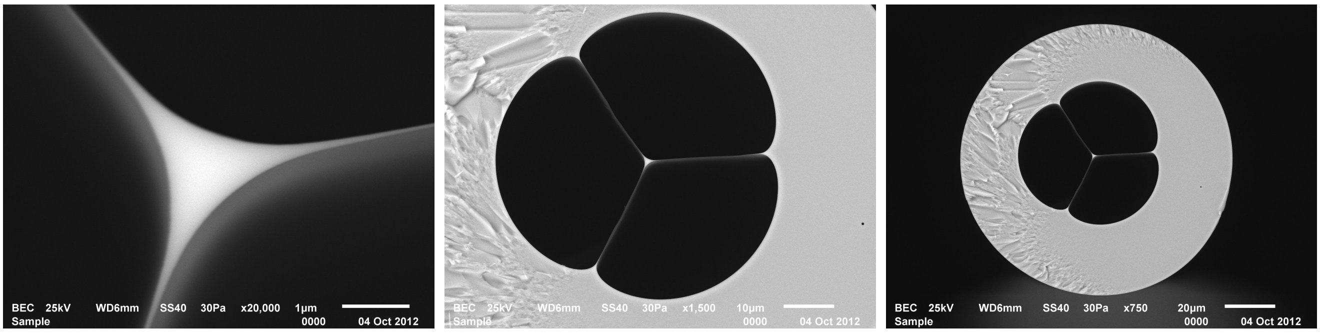

Figure 4: Cross sections of lead-bismuth-gallate SCF with details on core area, MOF structure and complete view of the fiber.

Further decrease of A_{eff} is possible to achieve by fiber tapering. Fiber tapering represents a process, when the optical fiber is heated to its melting temperature and then stretched with precise tension, thus producing a so called fiber taper. The taper has two transition regions and a waist with diameter $d_{waist} < d_{fiber}$. When the waist diameter is tapered under one micron the so called nanowires or nanotapers are produced. Recently fiber tapering extended from conventional fibers to microstructured and soft glass fibers. For these special applications the tapering process was modified and apart from heating over flame, CO_2 laser tapering has been utilized [41] or also ohmic heating has been employed [42].

AIMS OF THE DOCTORAL THESIS

Main objectives of the dissertation thesis are to propose a novel switching methodology for optical packet switching based on nonlinear optics. An innovative approach to optical packet switching will be presented based on analysis of state-of-art materials and advancements in fiber technology. Switching method employing nonlinear phenomenon will be studied theoretically and analytically. As the topic spans over an extremely wide research area several decisions have to be made, to keep the thesis focused on solving its main aim.

Major decisions:

- Only one switching fabric (MEMS, monolithically integrated or fiber-based) will be discussed for optical packet switching.
- Only one labelling technique (WDM, OTDM, etc.) will be analyzed.
- Only one switching technique (Broadcast-and-select, space-switching, etc.) will be exploited.
- 1xN or NxN switching scheme will be employed.

For the purpose of this thesis the choice was made for 1xN fiber-based wavelength routing switching scheme with the WDM labelling technique.

Based on the previous chapters the criteria for the new switching methodology have been then set as follows:

- Modulation format transparency
- Bitrate insensitivity
- Polarization insensitivity
- High-speed switching
- Switching efficiency
- Wavelength range
- Spectral efficiency

According to the above mentioned criteria and chosen methodology, following two chapters will be focused on the development of technological aspects of utilized optical fibers with enhanced nonlinearity and on the switching methodology. The most suitable approach will be analytically studied. A complete optical packet switch based on selected methodology will be constructed to enable wide range analyses.

The main thesis focuses can be therefore stated as:

- 1. Technological development of novel nonlinearity enhanced optical fiber and their optimization for optical packet switching.
- 2. Proposal and theoretical and experimental verification of the optical packet switching methodology.

WORKING METHODS

First step to fulfill the thesis objectives was the technological development, characterization and optimization of enhanced nonlinearity fibers. Two fibers were considered with highly-nonlinear fiber (HNLF) as a reference. The following single-mode fibers were chosen:

- HNLF
- Chalcogenide As_2Se_3 fiber (As_2Se_3 fiber)
- Suspended core silica fiber with highly Ge-doped core (Ge-SCF)

A suspended core silica fiber with highly Ge-doped core provided by IPHT, Jena, Germany, was exploited for the purpose of this thesis. Cross-section of utilized Ge-SCF is presented in Fig. 5 with the core diameter of 6.6μm, obtained by scanning electron microscope (SEM).

A splicing method has been developed for Ge-SCF connection to a conventional silica SMF-28e fiber. Almost negligible splice losses were obtained at 1550nm (<1 dB per splice). All these procedures were carried out in cooperation with SQS Fiber optics, Czech Republic, therefore exact technological processing steps cannot be mentioned in this thesis due to ongoing patent application.

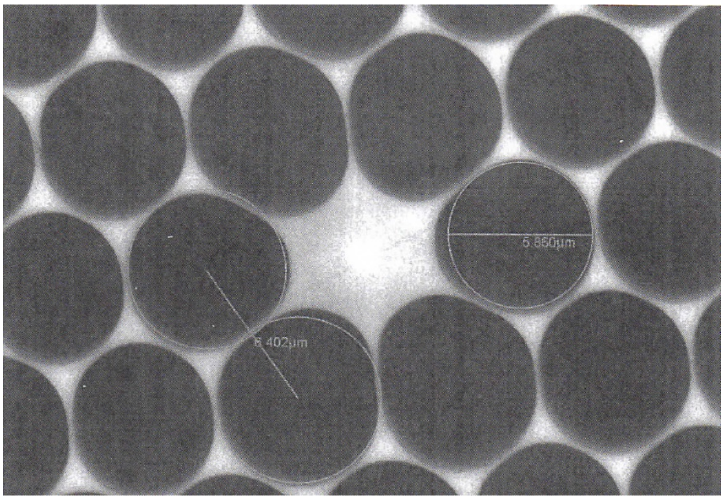

Figure 5: Cross-section of utilized Ge-SCF, manufactured at IPHT, Jena, Germany. Picture taken by SEM.

Chalcogenide As_2Se_3 single-mode fiber with single-mode cut-off at approximately ~1300nm has been employed in the latest measurements. Fiber attenuation was significantly reduced by the improved drawing technique.

The crucial part of As_2Se_3 fibers implementation lay in coupling of the propagated light from/to conventional silica SMF-28e fiber. As_2Se_3 fiber samples employed in this thesis provide refractive index of 2.8, which in contrast to ~1.46 of silica causes connection loss of ~20% at each boundary. Methods utilizing free-space optics (FSO) to couple light from silica to chalcogenide fibers were avoided in this thesis. In Fig. 6 facets of three damaged flat polished connectors from our development stage are presented, illustrating fragility of the chalcogenide fiber. Recently a technological process for chalcogenide connectorization was mastered at SQS Fiber optics, Czech Republic and is currently being patented. This was achieved by employing antireflex coating decreasing the detrimental effect of the refractive index difference (<1% reflection in the C-band), where reduced connection losses were observed (<1dB per connection).

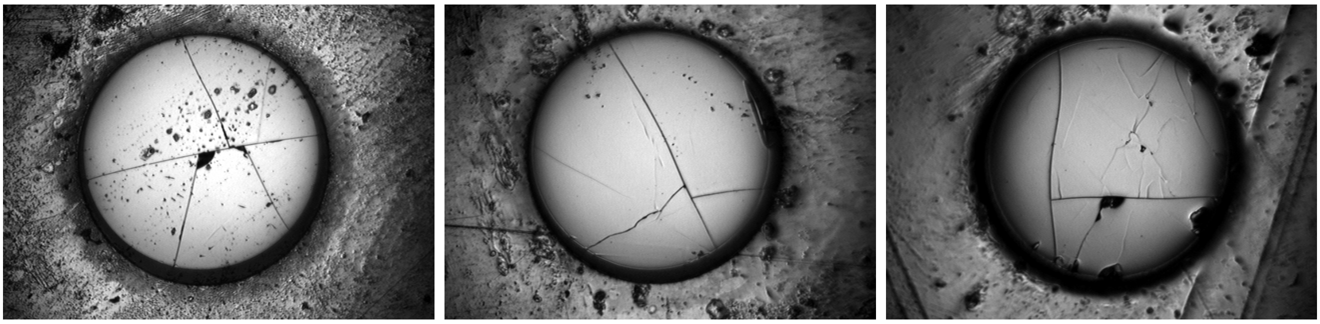

Figure 6: Facets of As_2Se_3 fiber samples damaged during the connectorization process.

A final component containing 26m As_2Se_3 fiber spool with standard silica SMF-28e fibers at output was developed. Insertion loss of 15.5 dB for the whole component was obtained. From this results one extremely important fact. We have developed a component with SMF-28e compatible outputs formed by As_2Se_3 fiber with attenuation lower than the value provided by manufacturer. This leads to fiber attenuation of less than 0.6dB/m, which is the lowest value for a As_2Se_3 single-mode fiber reported world-wide up to date (according to authors knowledge). It is then possible to develop As_2Se_3 components of ∼1m lengths with insertion loss <3dB, which is important for nonlinear processes.

Nonlinear coefficient estimation

To exactly measure nonlinear coefficient of evaluated fibers a method utilizing FWM [43] was employed. First application of the measurement technique focused on HNLF to verify the selected approach. The manufacturer of utilized HNLF provided nonlinear coefficient value of 11.5 $W^{-1}km^{-1}$. We have measured γ of 11.35 $W^{-1}km^{-1}$, thus verifying the method. Figure 7 illustrates one of the measured spectra for nonlinear coefficient estimation via the FWM method.

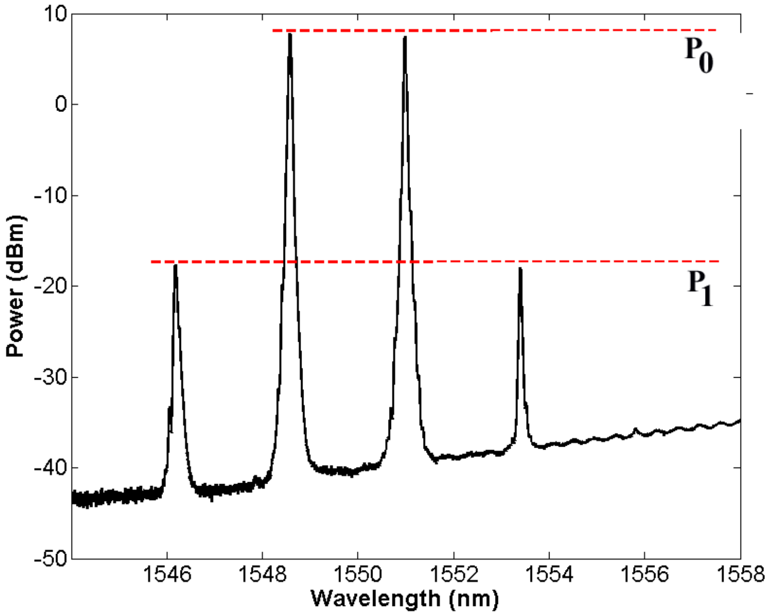

Figure 7: Measured FWM spectrum for nonlinear coefficient estimation.

For the As_2Se_3 fiber γ of 1300 $W^{-1}km^{-1}$ was measured. Ge-SCF was not measured by the FWM method and for further evaluations γ of 21 $W^{-1}km^{-1}$ was considered.

SPM measurements

For nonlinear response evaluation of chosen fibers the SPM effect was measured. Pump peak powers were set in range from 3 to 13dBm. For Ge-SCF no spectral broadening was observed. As_2Se_3 showed broadening of only several nanometers. HNLF spectral broadening over 100nm depicted in Fig. 8 resulted from HNLF flat dispersion profile and normal dispersion regime.

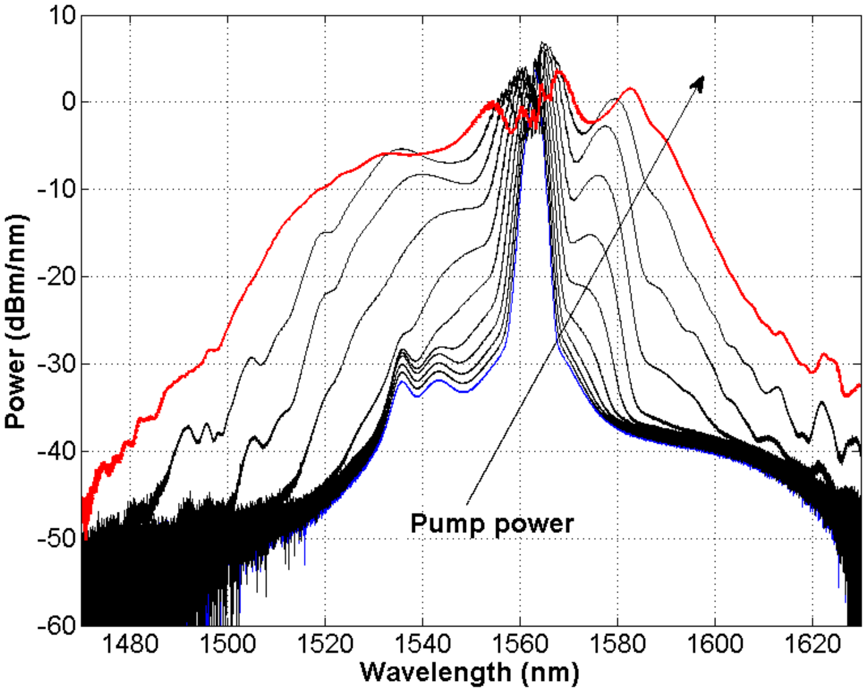

Figure 8: SPM spectral broadening in 500m HNLF.

Chalcogenides thermal tests

For material study for temperature range from -70°C to +110°C a multimode As_2Se_3 fibers with 172μm core and 330μm polymer cladding was utilized, where obtained results can be transferred to the As_2Se_3 single-mode fiber employed in the proposed optical packet switching methodology. Measured samples of relative loss change were obtained for each 10°C step after reaching thermal equilibrium. Relative loss deviation from the reference value in the studied temperature range was under 1dB/m, which implies maximum As_2Se_3 single-mode fiber attenuation of ~1.5dB/m.

Arrayed-waveguide grating development

AWGs were developed at SQS Fiber optics, Czech Republic [44, 45] and were able to work at room temperature without any detuning. AWGs with 44 channels placed 100GHz apart on the ITU-grid were employed. For final application athermal-AWG (AAWG) were developed (for operation principle of AAWG see e.g. [46]). They provided thermal stability in the range of -40 to +80°. Functional samples for the AWG and AAWG were applied to provide legal protection.

RESULTS

Preliminary experimental setup of the hybrid OPS for testing of the switching methods and nonlinear fibers is depicted in Fig. 9. Developed OPS consisted of four functional segments. First segment was composed of a payload generator, label generator and a multiplexer forming the optical packet. The generated optical packet was then propagated through a network segment and then the label was separated. Second segment was responsible for payload buffering. Third segment detected and processed the packet label and governed routing signal generation. Afterwards the buffered payload was multiplexed with the routing signal. In the fourth section propagation through the nonlinear fiber and a new label attachment took place.

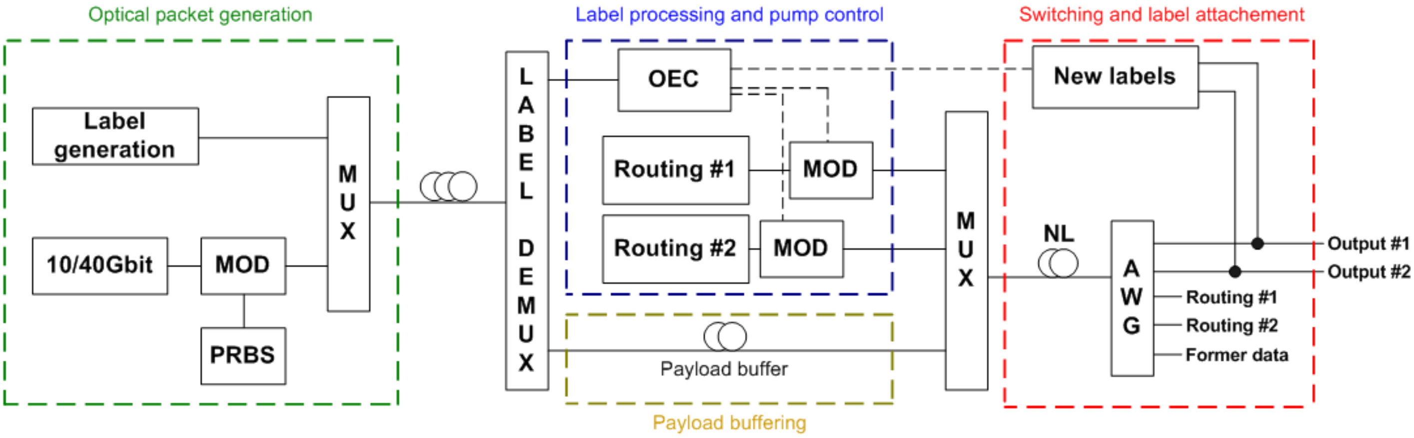

Figure 9: Proposed OPS setup, MOD - Mach-Zehnder modulator, OEC - opto-electronic controller, NL - nonlinear fiber.

Optical packet generation

Data laser allocated on the 100GHz DWDM ITU-grid was externally modulated with a pseudo-random binary sequence (PRBS), thus forming the optical packet payload. In bit-error-rate (BER) measurements, the laser was replaced by a BER tester (BERT). For label generation small form-factor pluggable (SFP) modules placed on the CWDM grid, providing labels with slow modulation (∼MHz) at wavelengths not coinciding with the data spectrum were employed. The label generated by the SFP module carried 8 bits with a 100MHz modulation, which implied label length of 80ns. Two different bit sequences were utilized to distinguish output ports. For payload and label coupling either a standard coupler, a wavelength multiplexer or AWG could be employed.

Opto-electronic control unit

For this thesis the hybrid opto-electronic approach for label processing was utilized. Opto-electronic controller (OEC) exhibited fast transient response lower than 5ns. For routing signal generation distributed feedback (DFB) laser diodes with 10MHz line-width and internal cavity tuning were employed. Their operational wavelength sensitiveness to both temperature and injection current is a well-known phenomenon, but as they provide high output optical powers (∼18dBm) in contrast to other laser diodes, this disadvantage required solving. To eliminate this temperature dependence external modulation was carried out via Mach-Zehnder amplitude modulators (MODs) controlled by OEC. These modulators, thanks to their nonlinear response to control current, provided switching speed of less than 3ns in contrast to the switching speed of the whole OEC.

Evaluation of the switching methodology

Numerous aspects were considered, evaluated and parametrized to achieve efficient optical packet switching, insensitive to states of polarization and with acceptable BER and OSNR values.

The optimization of the switching elements was carried out according to the following criteria: nonlinearity, component insertion loss, length and SBS limits. For this purpose three sample fibers were prepared, measured and evaluated to provide comparable parameters (for technological details see Chapter 6).

- 500m HNLF
- 100m Ge-SCF
- 26m As_2Se_3

Following table summarizes material losses given by manufacturer and whole component measured losses (with connection to standard SMF-28e fiber).

Fiber	$\alpha_{material}$ [dB/m]	$\alpha_{component}$ [dB]
500m HNLF	$7{\cdot}10^{-4}$	0.55
26m As_2Se_3	0.5	15.50
100m Ge-SCF	0.04	6.10

SBS measurements

From calculations for 500m long HNLF the SBS threshold was verified by measurements at 12dBm peak power, i.e. 15mW. For the As_2Se_3 fiber the SBS threshold was observed at 16dBm, which corresponds with calculated theoretical value. Significant backreflected power was present for As_2Se_3 in the whole pump tuning range due to the large refractive index contrast at As_2Se_3/silica boundary. In contrast to the As_2Se_3 and HNLF, there was no observed SBS backscattered power for the Ge-SCF, but is expected to appear at 26dBm pump peak power.

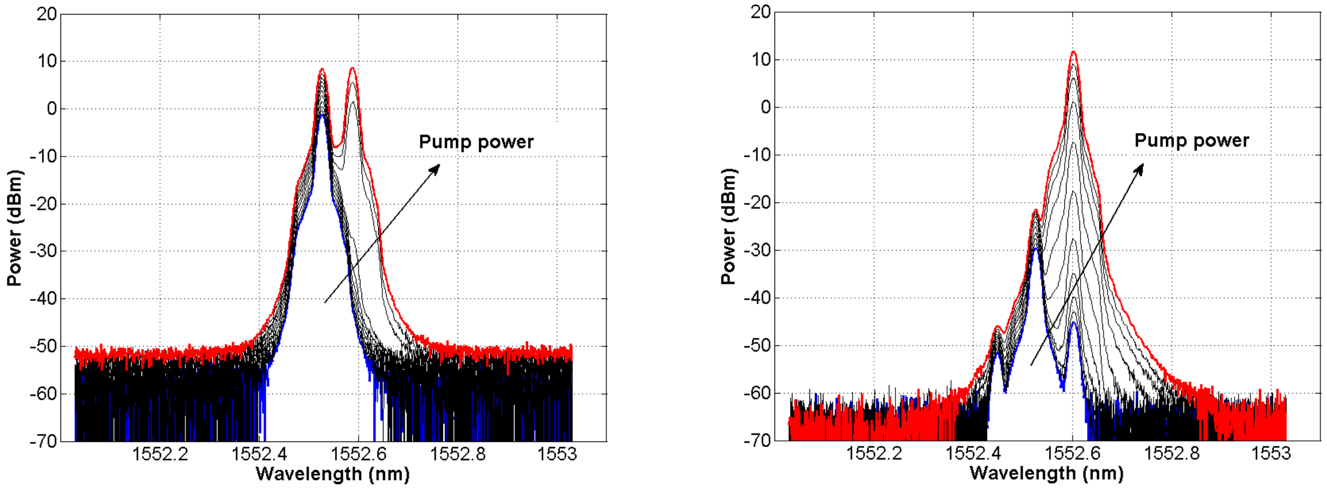

Figure 10: SBS backscattered spectra - 26m As_2Se_3 (left) and 500m HNLF (right), pump power 6dBm (blue) to 16dBm (red).

Conversion efficiency

Wavelength conversion efficiency is independent of data payload power, therefore only pump power plays the critical role. In this case it is limited by the SBS effect (HNLF at 13dBm, As_2Se_3 at 16dBm and Ge-SCF at 26dBm). For initial comparison, all three evaluated nonlinear fibers were tested at +1 channel detuning from the pump (considering DWDM 100GHz ITU-grid). Almost no converted idler was present for Ge-SCF, therefore further employment in the OPS was not considered. As_2Se_3 fiber conversion efficiencies were under -40dB, where the major detrimental effect was implied by the component insertion loss. HNLF measurements are presented in Fig. 11 with conversion efficiencies exceeding -20dB for pump peak powers over 12dBm. Additional measurements were carried out to evaluate HNLF conversion efficiency within wider wavelength range. In Fig. 11 conversion efficiency in dependence on channel detuning is presented with pump allocation at 1552.52nm and with peak powers of 3dBm, 8dBm and 13dBm.

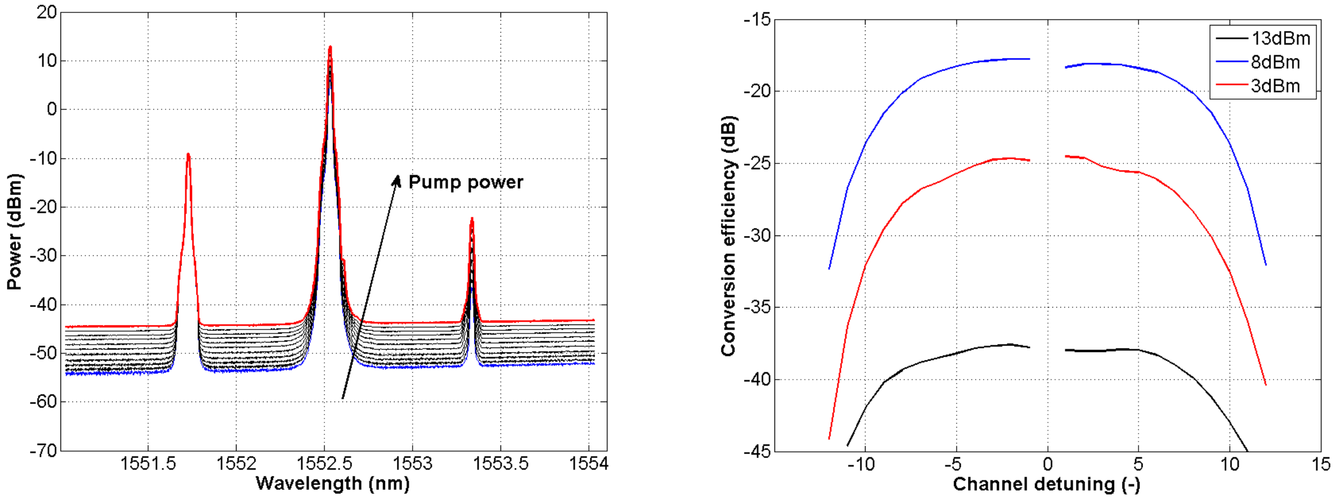

Figure 11: Four-wave mixing in 500m HNLF (left) - pump power from 6dBm (blue) to 16dBm (red). Conversion efficiency in dependence on channel detuning (right)

Frequency plan

Based on the results from conversion efficiency measurement HNLF was considered for further application for optical packet switching. Attention was paid to facile routing signals and former data filtering, maximum conversion efficiency and frequency plan scalability. The final setup is illustrated in Fig. 12 with routing signals placed +3/+4 channels from the data payload. Generated idlers are then at +6/+8 channels from the former data signal.

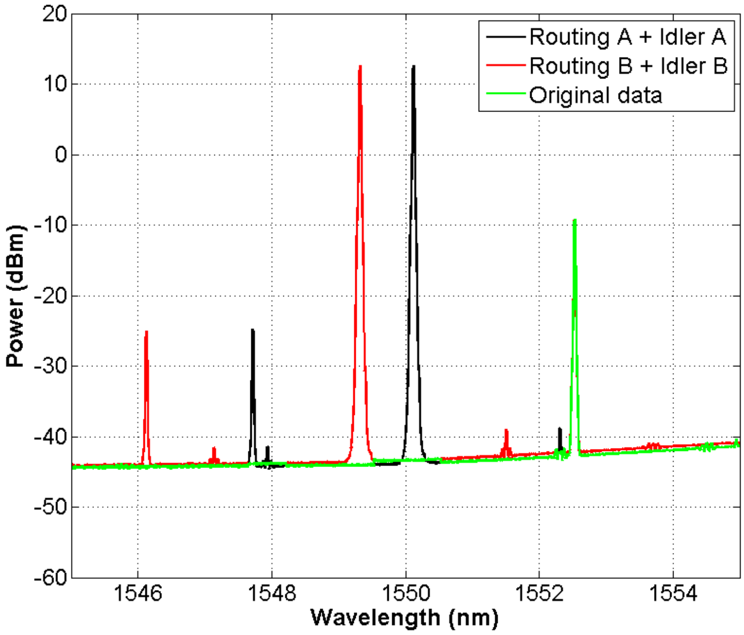

Figure 12: Final frequency plan for FWM-based optical packet switching.

Polarization insensitivity

For this thesis a setup incorporating a circulator (CIRC) and PBS was selected. In Fig. 13 a setup of this configuration is depicted. The fiber under test (FUT] was placed in a loop and PBS divided the signals into fast and slow axes. The only critical condition was to keep the pump polarization in 45° to the slow axis of PBS, so that the pump power was equaly divided into the clockwise and counter-clockwise directions. Then the pump and signal were filtered (via BF #2 and AWG) and only idler was detected at optical spectral analyzer (OSA).

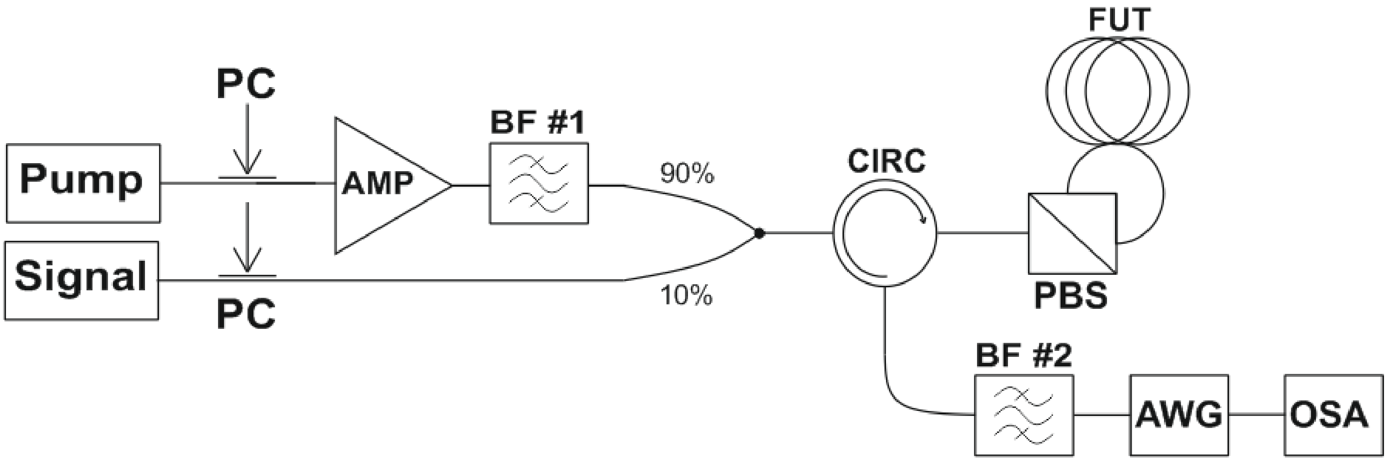

Figure 13: Polarization insensitive configuration.

Polarization state of the signal was then varied in a 90° range with maximal difference in conversion efficiency of +/-0.6dB. When the state of polarization was varied in the polarization sensitive setup, the idler peak power values decreased rapidly according to the simulated results depicted in Fig. 14.

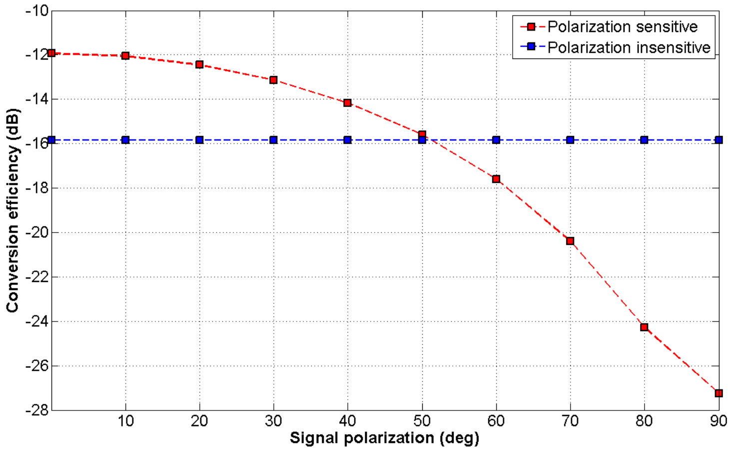

Figure 14: Simulated conversion efficiency in HNLF, pump polarization is tuned by +0° to +90° from the data signal.

BER tests

A 10Gbps NRZ BERT was utilized as the data payload source in the same configuration as depicted in Fig. 13 for the polarization insensitive variant. Unfortunately no signal was detected at the BERT receiver when the pump peak power was tuned from 6dBm to 16dBm. The reason lay in too low data signal power after the wavelength conversion (around -30dBm, when considering -10dBm data signal before the HNLF). To counter this effect, EDFA was moved directly before the HNLF and instead of the 90/10 coupler a WDM-MUX was employed. Even with these changes, no signal was detected by the BERT receiver. It was necessary to further amplify the converted data signal by a power-booster (PB) and slightly change the filtering stage composition. The innovated polarization insensitive configuration is depicted in Fig. 15.

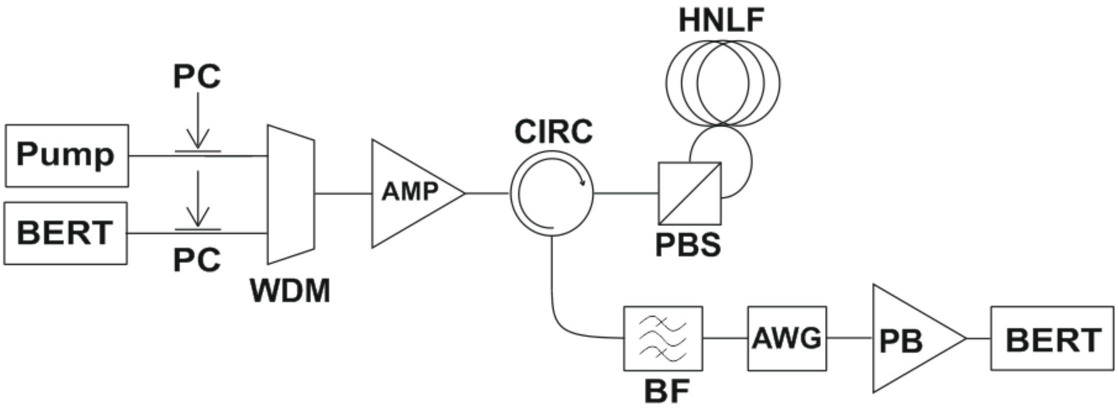

Figure 15: Innovated polarization insensitive setup for BER measurements.

The highest BER of 10^{-12} was achieved at 17dBm total EDFA power, whereas for 16 and 18dBm BER better then 10^{-10} was observed. Eye-diagram of the best BER is depicted in Fig. 16, with 8.23dB extinction ratio and a clear eye-opening. Measured in-band OSNR and extinction ratios for different EDFA total powers are presented in Fig. 17.

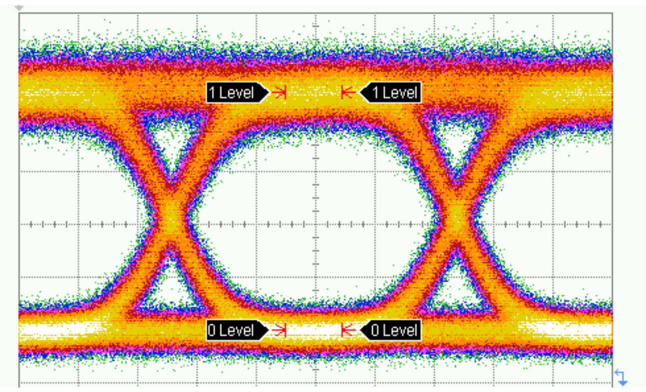

Figure 16: Eye-diagram of 10Gbps NRZ switched data signal, 8.23dB extinction ratio.

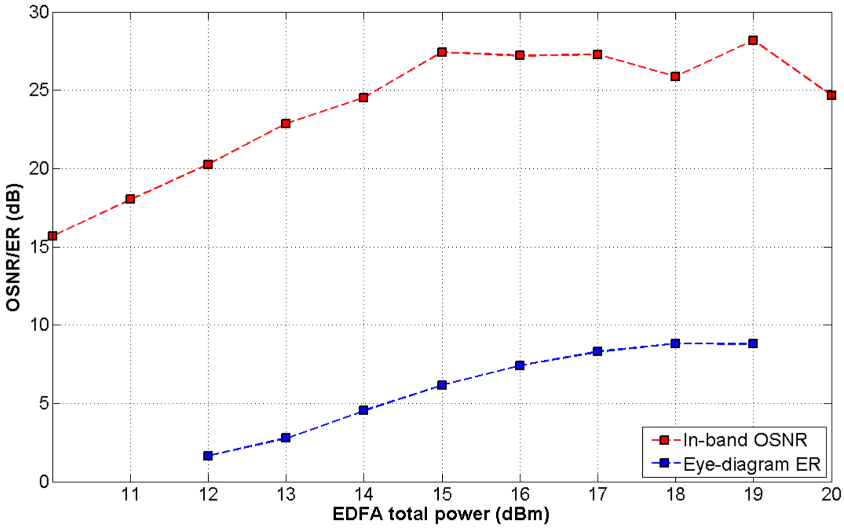

Figure 17: In-band idler OSNR and eye-diagram extinction ratios (ER) for different EDFA total powers.

Modulation format transparency

Advanced modulation formats are expected in future OPS applications. With achieving polarization insensitive wavelength conversion and utilization of the proposed frequency plan, the identical configuration was employed for simulations. Theory of FWM predicts modulation format transparency for PSK and QAM signal wavelength conversion. Analytical verification was performed in OptiSystem for one polarization state of 100Gbps DP-QPSK as presented in Fig. 18, where the constellation diagram of the switched signal showed only small distortion. The same quality of results was obtained for 4-QAM, where additional polarization control was required to conserve the switching performance. Therefore the proposed methodology and OPS configuration can be utilized for novel modulation formats.

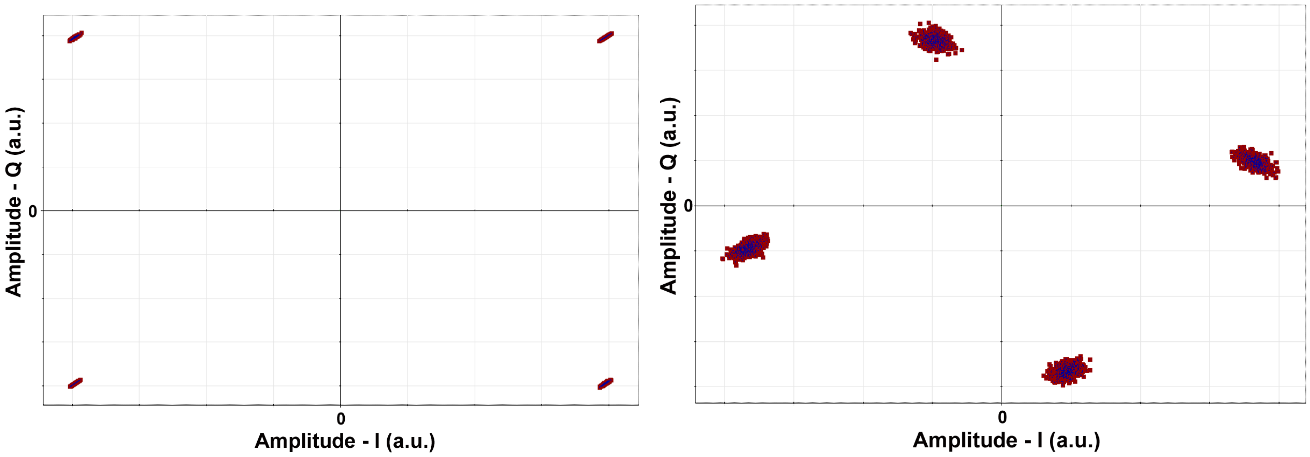

Figure 18: 100Gbps DP-QPSK constellation diagram before (left) and after (right) wavelength conversion.

Finalized OPS methodology

Based on previous analyses, optimizations, measurements and technological improvements a finalized OPS configuration is proposed (see Fig. 19). DFB diodes can be utilized as continuous-wave pumps (routing #1, #2 to #*n*), their polarization state has to be adjusted to 45° with respect to the PBS slow axis by a polarization controller (PC). Then they are modulated in a Mach-Zehnder modulator (MOD) controlled by OEC according to the label content. Routing signal and data payload are then multiplexed (WDM) and EDFA amplified (AMP). As the switching fabric HNLF was selected, which proved most suitable according to measurement results, and was included in a polarization insensitive fiber loop composed of a polarization beam splitter (PBS) and a circulator (CIRC). Generated idler is then filtered by a bandpass filter (BF) and AWG and afterwards amplified in a power-booster (PB). New label is generated by SFP and attached to the switched data payload.

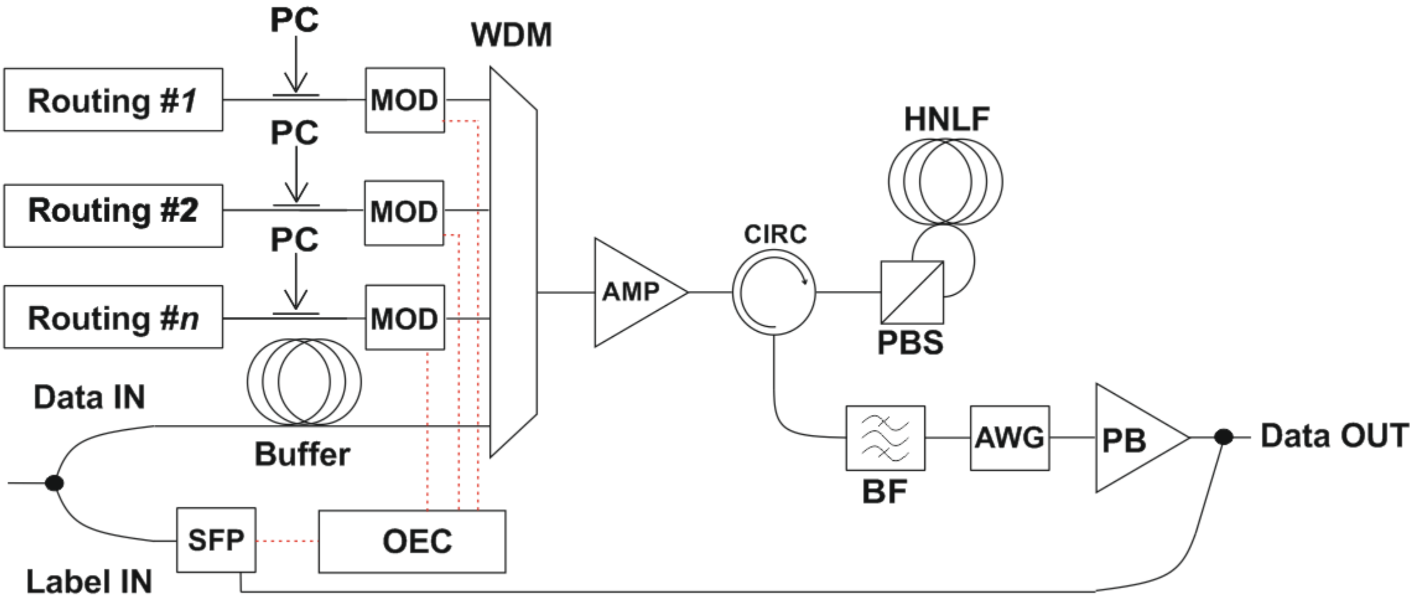

Figure 19: Final OPS configuration with n routing signals, payload buffer and OEC modulator control.

CONCLUSION

The dissertation thesis was focused on optical packet switching based on nonlinear optics. To fulfill the aim of the thesis, an analysis of various OPS state-of-art aspects was carried out with the decision for a fiber-based optical packet switch. Consequently nonlinear optics with the focus on optical fibers were discussed. Theoretical background and basic principles of fiber-based switches were presented. Afterwards the state-of-art technological aspects of nonlinear fibers were summarized with the emphasis on various approaches of achieving higher nonlinear coefficient.

The two main thesis objectives were then selected. One with the aim of proposing a new switching methodology for optical packet switching and the other with the emphasis on technological aspects of nonlinear fibers and their preparation and optimization for the proposed methodology.

Advancements in technological aspects of nonlinear fibers were presented, where a conventional HNLF was employed to enable comparison with the other utilized enhanced nonlinearity fibers. A single-mode arsenic-selenide fiber with cut-off at 1300nm was connectorized and a component with 26m length was developed. Attenuation lower than 0.6dB/m was obtained with connection losses under 1dB, thus presenting enhancement of current state-of-art parameters. Ge-doped suspended-core fiber was evaluated as a representative of microstructured fibers, with nonlinear coefficient twice the HNLF. Splicing technology was developed and a 100m component was produced with approximately 6dB insertion loss. Chalcogenide tapering was also studied and a technological process was mastered, but utilizable samples were not prepared by the time of the thesis finalization. Chalcogenide As_2Se_3 and microstructured Ge-SCF technological connectorization processes were finalized and are currently being patented. Athermal AWGs are in pilot production.

Afterwards the development of the switching methodology was presented. First an opto-electronic controller was developed for label processing, achieving less than 5ns switching time. Routing signals were generated by DFB diodes, which proved to be thermally dependent, therefore they were externally modulated by Mach-Zehnder modulators controlled by OEC. New label generation was ensured by the SFP module and could be synchronously attached to the switched packet.

Conversion efficiencies were measured for all utilized fibers, where the best results were obtained for HNLF. Conversion efficiency for the As_2Se_3 fiber was below -40dB due to the high component insertion loss. Ge-SCF showed almost no nonlinear response, which was expected, as the nonlinear length was higher than the effective length, therefore it was discarded from the final OPS setup. As_2Se_3 fiber would require further optimization to provide better switching parameters than HNLF, mainly length reduction to decrease insertion loss. With length reduction of As_2Se_3 fiber the SBS treshold will increase, which gives As_2Se_3 an advantage over HNLF in future enhancement of the proposed optical packet switching methodology.

HNLF was employed for optical packet switching, with modulation format transparent switching, eight channels flat conversion efficiency profile and polarization insensitive operation in the final proposed switching methodology configuration. On the other hand SBS tresholds for HNLF were the lowest of all utilized fibers.

To conclude, a functional optical packet switch methodology was developed based on enhanced nonlinearity optical fiber. BER tests were performed for the polarization insensitive configuration with extinction ratio of more than 8dB for the best eye-diagrams. BER better than 10^{-10} was observed. Modulation format transparency for DPSK, DP-QPSK and QAM was verified only in simulations with results indicating functionality of proposed switching methodology and OPS configuration. In-band OSNR measurements proved good signal resolution. Currently our proposed optical packet switching methodology is being applied as a utility model.

For future research, focus will be paid on As_2Se_3 and lead-silicate fibers. They will be considered both in conventional and microstructured design and will be optimized to provide better efficiencies than HNLF, while minimizing component insertion loss. Conversion efficiency of more than -10dB is desired.

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Publikace v impaktovaných časopisech:

Publikace v recenzovaných časopisech:

Patenty:

1. Komanec, M. (33%), Škoda, P., Zvánovec, S.: Optický vláknový laser. [Funkční vzorek]. 2011.

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Procentuální podíl všech spoluautorů u uvedených publikací je rovnoměrný.

Summary

The dissertation thesis was focused on optical packet switching based on nonlinear optics. To fulfill the aim of the thesis, an analysis of various optical packet switching state-of-art aspects was carried out with the decision for a fiber-based optical packet switch. State-of-art technological aspects of nonlinear fibers were summarized with the emphasis on various approaches of achieving higher nonlinear coefficient.

A single-mode arsenic-selenide fiber with cut-off at 1300nm and nonlinear coefficient over 1000 $W^{-1}km^{-1}$ was connectorized and a component with 26m length was developed. Attenuation lower than 0.6dB/m was obtained with connection losses under 1dB, thus presenting enhancement of current state-of-art parameters. Ge-doped suspended-core fiber was evaluated as a representative of microstructured fibers, with nonlinear coefficient of $21W^{-1}km^{-1}$. Splicing technology was developed and a 100m component was produced with approximately 6dB insertion loss. Technology of the connectorization process is currently being patented.

Afterwards the development of the switching methodology was presented. First an opto-electronic controller was developed for label processing, achieving less than 5ns switching time. Then conversion efficiencies were measured for all utilized fibers, where the best results were obtained for HNLF at -15dB. Conversion efficiency for the As_2Se_3 fiber was below -40dB due to high component insertion loss. Ge-SCF showed almost no nonlinear response.

Based on the results a frequency plan was proposed employing HNLF. Modulation format transparent switching, sixteen channels flat conversion efficiency profile and polarization insensitive operation in the final proposed switching methodology configuration was achieved. BER and OSNR values verified operation at 10Gbps NRZ, where for 40Gbps DPSK and 100Gbps DP-QPSK the verification was carried out in simulations.

Resumé

Disertační teze byla zaměřena na optické paketové přepínání založené na nelineární optice. Ke splnění cílů teze byla provedena analýza různých aspektů stavu techniky pro optické paketové přepínání s volbou optického paketového přepínání založeného na vláknech. Stav techniky technologických aspektů nelineárních vláken byl shrnut s důrazem na rozličné přístupy dosažení vyššího nelineárního koeficientu.

Jednovidové arsen-selenové vlákno s vlnovou délkou jednovidovosti 1300nm a nelineárním koeficientem přes 1000$W^{-1}km^{-1}$ bylo konektorováno a byla vyvinuta komponenta o délce 26. Byl dosažen útlum menší než 0.6dB/m se ztrátami na spoji menšími než 1dB, což znamená vylepšení parametrů současného stavu techniky. Ge-dopované suspended-core vlákno bylo zkoumáno jako zastupitel mikrostrukturních vláken s nelineárním koeficientem 21 $W^{-1}km^{-1}$. Byla vyvinuta svářecí technologie a byla vyrobena 100m komponentas přibližně 6dB vložných ztrát. Technologie konektorizačního procesu je v současné době patentována.

Následně byl prezentován vývoj přepínací metodologie. Prvotně byl sestrojen opto-elektronický kontrolér pro zpracování hlavičky, s přepínací dobou dosahující méně než 5ns. Poté byly změřeny konverzní účinnosti pro všechna použitá vlákna, kde nejlepších výsledků bylo dosaženo pro HNLF při -15dB. Konverzní účinnost As_2Se_3 byla nižší než -40dB vzhledem k velkým vložným ztrátám komponenty. Ge-SCF poskytlo minimální nelineární odezvu.

Na základě výsledků byl navržen frekvenční plán pro HNLF. Ve finální konfiguraci přepínací metodologie bylo dosaženo přepínání nezávislého na modulačním formátu, s plochou křivkou konverzní účinnosti přes šestnáct kanálů a nezávislého na stavu polarizace. Hodnoty BER a OSNR potvrdili funkčnost na 10Gbps NRZ a pro 40Gbps DPSK a 100Gbps DP-QPSK potvrzení bylo provedeno v simulacích.