Impact of Pump-Phase Modulation on FWM-Based Wavelength Conversion of D(Q)PSK Signals

Robert Elschnner, Student Member, IEEE, Christian-Alexander Bunge, Member, IEEE, Bernd Hüttl, Alexandre Gual i Coca, Carsten Schmidt-Langhorst, Reinhold Ludwig, Colja Schubert, and Klaus Petermann, Senior Member, IEEE

Abstract—We investigate both theoretically and experimentally the impact of pump-phase modulation on differential phase shift keying (DPSK) and differential quadrature phase shift keying (DQPSK) signals in fiber-based parametric wavelength converters. It will be shown that the pump-phase modulation used to suppress stimulated Brillouin scattering introduces critical signal degradation and optical SNR penalties on DPSK signals, and more severe on DQPSK signals. Different modulation schemes will be theoretically investigated and the quantitative results are compared to system experiments. Finally, the theoretical results for a single conversion will be extended to multiple conversions to study the cascadibility of the wavelength converter.

Index Terms—Differential phase shift keying (DPSK), differential quadrature phase shift keying (DQPSK), stimulated Brillouin scattering (SBS), wavelength conversion.

I. INTRODUCTION

WAVELENGTH converters are commonly accepted as key components for flexible all-optical network approaches like optical burst and packet switching [1], [2]. The wavelength converters are envisioned to fulfill multiple tasks inside the switching nodes and supposed to be involved in routing, contention resolution, and signal regeneration [3]–[5]. Due to this demand from the system side, components suitable to match all practical requirements are rare, although a large number of concepts have already been proposed based on different materials and nonlinear effects [6]–[10]. Among others, tunability, cascadibility, and transparency to bitrate and modulation formats are important characteristics of all-optical wavelength conversion to compete with optoelectronic solutions.

Fiber-based components relying on four-wave mixing (FWM) seem very promising to match, in particular, the two latter requirements. Wavelength conversion of 80 Gb/s differential quadrature phase shift keying (DQPSK) [11] and multiwavelength conversion of up to 40 Gb/s per channel differential phase shift keying (DPSK) signals have been shown [12], [13]. We recently presented all-optical wavelength conversion of 320 Gb/s differentially phase-modulated signals based on FWM in a highly nonlinear fiber (HNLF) [14], [15] where we used continuous-wave (CW) pumping to provide modulation format transparency. In addition to the well-known fact that stimulated Brillouin scattering (SBS) limits the conversion efficiency of CW pumped FWM processes leading to low cascadibility [16], also the impact of the pump-phase modulation in order to suppress SBS has been extensively investigated in the past years. Firstly, pump-phase modulation can generate signal gain distortions that depend on the rise/fall time of the optical modulator [17]–[21]. Secondly, it leads to detrimental spectral broadening and phase distortions of the wavelength-converted idler wave when using a single pump [22]. Although the latter obstacle can be overcome for a specific idler using two pump signals [23]–[26], applications using more than one idler [27], [28] or higher order idlers [29] are still affected.

In this paper, we will theoretically describe the impact of the induced phase distortions on the performance of DPSK and DQPSK signals in terms of the bit error rate (BER). Quantitative results for a single conversion are compared to our recent experiments and extended to multiple conversions to study the cascadibility. Our results give a lower bound of the achievable optical SNR (OSNR) penalty and will identify the induced phase distortions as a major degradation source when dealing with differentially phase-modulated signals.

This paper is organized as follows. In the second section, we briefly describe the limitations SBS sets on the efficiency of FWM. In the third section, we will discuss the phase distortions introduced by the pump-phase modulation. In the fourth section, we will theoretically derive the resulting OSNR penalty and compare the results with the recent experiments. Finally, in the fifth section, we will present results showing the cascadibility potential of the converter.

II. FOUR-WAVE MIXING IN HIGHLY NONLINEAR FIBERS

One of the most important features of the all-optical wavelength converter (AOWC) is low loss, which increases the cascadibility of the converter depicted in Fig. 1. Thus, the

Fig. 1. (a) Principle setup of the FWM-based AOWC. (b) Schematic output spectrum.
wavelength conversion must be as efficient as possible. In the case of perfect phase matching [7], the conversion efficiency is given by

$$\eta_C = \frac{P_1(L)}{P_S(0)} \approx \sinh^2(\gamma P_L L)$$

where $P_1$, $P_S$, and $P_P$ are the powers of the converted signal (also called idler), the input signal, and the pump signal, respectively. The other parameters are the nonlinear fiber coefficient $\gamma$ and the fiber length $L$. From (1), we could draw the conclusion that arbitrary high FWM efficiencies can be obtained by increasing the fiber length or the pump power. However, it is not as simple as it seems. The main problem for CW pumped FWM processes is SBS preventing high powers from propagating through the fiber [16]. The input power, above which the output power is saturating, is called threshold power $P_{th}$. For short fibers, it is approximately given by the expression [16]

$$P_{th} \approx \frac{21 A_{\text{eff}}}{g_B L}$$

where $g_B$ is the Brillouin gain coefficient, $A_{\text{eff}}$ the effective fiber core area, and $L$ the fiber length. It is inversely proportional to the fiber length, leading together with (1) to a fiber length independent available FWM efficiency that calculates to $-17$ dBm with the parameters given in Table I. This is clearly too low for a practical component.

### III. SUPPRESSION OF STIMULATED BRILLOUIN SCATTERING

Several strategies to bypass the SBS limit can be found in the literature [7], [31], [32]. One of the most effective and simple is to phase modulate the pump wave. The spectral distribution into sidebands decreases the amount of power within the Brillouin bandwidth $\Delta \nu_B$, and consequently, enhances the Brillouin threshold. In Fig. 2, the reflected power and the equivalent Brillouin threshold power as a function of the modulation frequency with modulation index $m_1 = 2.5$ rad and input power $P_{in}^1 = 14.5$ dBm. Parameters for the theory after [30] are given in Table I.

$$\phi(t) = 2\phi_P(t) - \phi_S(t) + \frac{\pi}{2}$$

where $\phi_P$ and $\phi_S$ are the phases of the pump and the input signal at the fiber input, respectively. For differentially phase-modulated signals like DPSK and DQPSK, a time-dependent pump phase directly changes the phase difference between consecutive pulses and leads to a differential phase distortion in the idler wave given by

$$\Delta \phi_{\text{mod}}(t) = 2[\phi_P(t + T_{\text{Bit}}) - \phi_P(t)]$$

with $T_{\text{Bit}}$ the length of a bit slot. In the literature, the most commonly used modulation signals are, first, binary phase-shift keying (BPSK) signals with a pseudorandom bit sequence [7], and second, a multifrequency scheme using several sinusoidals [33]. With regard to (4), the first scheme has the problem to keep the BPSK phase transitions out of the input signal bit slot otherwise destroying the phase information. Sufficiently fast rise times will be difficult to achieve for the envisaged optical bitrates and the required synchronization to the input signal clock is at least impractical for single-channel applications and impossible for multichannel applications where every channel has a different clock displacement [34]. For these reasons, the BPSK scheme is not applicable for the conversion of differentially phase-modulated signals and will not be considered further.

To account for the multifrequency scheme, we assume at first a modulation with two sinusoidals (dual-tone scheme). Then, the complex amplitude of the pump signal at the fiber input is given by:

$$P_{1h} = \frac{21 A_{\text{eff}}}{g_B L}$$

where $g_B$ is the Brillouin gain coefficient, $A_{\text{eff}}$ the effective fiber core area, and $L$ the fiber length. It is inversely proportional to the fiber length, leading together with (1) to a fiber length independent available FWM efficiency that calculates to $-17$ dBm with the parameters given in Table I.
given by
\[ A_P(t) = \sqrt{P_p^{\text{in}}} \exp \left[i m_1 \cos(2\pi f_1 t) + im_2 \cos(2\pi f_2 t)\right] \quad (5) \]
and is characterized by its power \( P_p^{\text{in}} \), the two modulation frequencies \( f_1 > f_2 \), and the two modulation indices \( m_1, m_2 \). For the case that the line rate \( B = 1/T_{\text{Bit}} \) is much higher than the maximal modulation frequency, \( B \gg f_1 \), we can approximately calculate the maximal differential phase distortion introduced by the pump-phase modulation:
\[ \Delta \phi_{\text{mod}}^{\text{max}} \approx 4\pi \left( m_1 f_1 + m_2 f_2 \right) B. \quad (6) \]

The interpretation of (6) is twofold. To keep the maximal phase distortion in the dual-tone scheme low, the maximal modulation frequency is limited to rather low values compared to the line rate, since \( m_1, m_2 \) should be chosen approximately equal to obtain an advantageous spectral distribution. Furthermore, to achieve the same maximal phase distortion for a single-tone scheme \((m_2 = 0)\) and for a dual-tone scheme, the modulation indices in the latter case have to be reduced. These qualitative conclusions also stay valid for multifrequency schemes using more sinusoids and make them ineffective in SBS suppression for the wavelength conversion of differentially phase-modulated signals. For this reason, we restrict the quantitative discussions in the following section to single- and dual-tone schemes.

IV. RESULTS FOR A SINGLE CONVERSION

In this section, we will calculate the conversion efficiency and the OSNR penalty connected with the phase distortion as functions of the pump-phase modulation for DPSK and DQPSK signals with a line rate of 40 Gbd.

A. Conversion Efficiency

The pump-phase modulation spectrally distributes the pump power, and thus, reduces the amount of power participating in the (narrowband) process of SBS. We calculate this reduction by shifting a Lorentzian lineshape filter with a bandwidth \( \nu_B = 40 \) MHz along the modulated pump spectrum and measure the collected amount of power. This is mathematically equivalent to a convolution of the modulated pump spectrum \( A_P(f) \) and the filter lineshape function \( H_{\text{Loc}}(f) \). The ratio between the maximum of the collected power and the total power denotes the reduction of the pump power participating in SBS. Its inverse can be interpreted as an increase of the Brillouin threshold power
\[ \Delta P_{\text{th}} = \frac{P_p^{\text{in}}}{\max \left[ A_P(f) * H_{\text{Loc}}(f) \right]^2} \quad (7) \]
where the asterisk accounts for the convolution. Inserting \( P_P = P_{\text{th}} + \Delta P_{\text{th}} \) from (2) and (7) into (1) gives the maximal conversion efficiency in dependence on the pump-phase modulation parameters. In Fig. 3, the results as a function of the modulation indices are shown for the single- and the dual-tone schemes. The nonmonotonic behavior of the curves is due to the change of the dominating harmonic with increasing modulation index. Following the discussion in Section III, we have chosen the modulation parameters in order to provide a fair comparison in terms of the maximal phase distortion. Therefore, the modulation indices of the dual-tone scheme have been set half of the modulation index of the single-tone scheme. Furthermore, to keep the phase distortion low, the modulation frequency \( f_1 = 100 \) MHz of the single-tone scheme is chosen as low as possible for sufficient SBS suppression (see Fig. 2).

For the dual-tone scheme, two curves are shown with the modulation frequencies \( f_1 = 100 \) MHz, \( f_2 = 60 \) MHz (DT A) and \( f_1 = 200 \) MHz, \( f_2 = 120 \) MHz (DT B). The ratio \( f_2/f_1 \) is kept constant at its value 0.6, which has been found to be optimal. While the scheme DT B provides an advantage in conversion efficiency in comparison to the single-tone scheme, the advantage is substantially reduced for the scheme DT A that provides nearly the same maximal phase distortion as the single-tone scheme. This is necessarily due to the small frequency spacing of the modulation frequencies and supports the conclusions drawn in Section III. Thus, the conversion efficiency cannot be increased arbitrarily if in the same time, the phase distortion has to be kept low.

B. Phase Distortion

In the next step, we want to quantify the phase distortion resulting from the pump-phase modulation. Using unmodulated pulses, a simple measure for that is the extinction ratio (ER) defined as the ratio of the received power in the upper arm of a balanced receiver and the received power in the lower arm
\[ \text{ER} = \frac{\langle 1 + \cos [\Delta \phi_{\text{mod}}(t) + \Delta \phi_0] \rangle}{\langle 1 - \cos [\Delta \phi_{\text{mod}}(t) + \Delta \phi_0] \rangle} \quad (8) \]
with \( \Delta \phi_0 \) the inherent phase error of the delay line interferometer [35] and the brackets denote time averaging over one period of the pump-phase modulation. The advantage of the ER is that it is experimentally very easily accessible. In Fig. 4, experimental results using 40 GHz pulses as input signal and different pump
The interferometer phase error was set to $\phi_0 = 0.32$ rad and the modulation index to $m_1 = 2$ rad. For the experiment, unmodulated 40 GHz pulses have been used as input signal. The theoretical curve has been obtained using (8) with $\phi_0 = 0.32$ rad.

powers and the analytically obtained result only using (4) and (8) are compared for the single-tone scheme. The interferometer phase error was set to $\phi_0 = 0.32$ rad and the modulation index to $m_1 = 2$ rad. The theory and the experiment fit very well over the upper modulation frequency range where the phase distortion induced by the pump-phase modulation is the dominant degrading effect. For small modulation frequencies, the low Brillouin threshold limits the available pump power. In this region, the low OSNR is the dominant degrading effect that is not included in (8). A maximum ER is obtained for $f_1 \approx 100$ MHz. A closer look at Fig. 4 reveals differences for the three pump powers. For $P_{\text{in}} = 14.5$ dBm, the ER is the lowest for nearly all modulation frequencies due to the lowest conversion efficiency limiting the OSNR. The ER for $P_{\text{in}} = 19.5$ dBm, well above the threshold, is degraded by SBS. The optimum pump power 17.5 dBm is just at the Brillouin threshold.

### C. OSNR Penalty

Having quantified the phase distortion induced by the pump-phase modulation, we now want to calculate the corresponding OSNR penalty as the most important parameter for the system design. Following Section IV-B, we can interpret $\Delta \phi_{\text{mod}}(t)$ given in (4) as a time-dependent additional interferometer phase error. The average BER is then given as a summation over all possible BER within one pump-phase modulation period $T_{\text{PM}}$:

$$\langle \text{BER} \rangle = \frac{1}{T_{\text{PM}}} \int_0^{T_{\text{PM}}} \text{BER} [\Delta \phi_0 + \Delta \phi_{\text{mod}}(t)] \, dt. \quad (9)$$

Now, we can use the analytical formulas proposed by [36] to obtain the OSNR penalty for DPSK and for DQPSK signals. The results for single-tone modulation with $m_1 = 2.5$ rad and dual-tone modulation with $m_1 = m_2 = 1.25$ rad is given in Fig. 5(a). The interferometer phase error was set again to $\Delta \phi_0 = 0.32$ rad to match the experimental conditions. The quantitative impact of this choice on the results is minor. The penalties quickly increase with increasing modulation frequency as it was indicated by the discussion for the ER. Being more phase sensitive due to the smaller Euclidian distance of the signal states, the DQPSK penalty grows faster than that for the DPSK signal. Furthermore, the dual-tone scheme leads to slightly lower penalties due to the fact that the maximal phase distortion is slightly lower and also occurs more seldom. In Fig. 5(b), the experimentally obtained power penalty for a DQPSK signal and a single-tone scheme with $P_{\text{in}} = 15$ dBm, $m_1 = 2.5$ rad, and $f_1 = 100-400$ MHz and the calculated OSNR penalty for the same case are shown; for better comparison, both penalties are given relative to their value at $f_1 = 100$ MHz. The dependency on the modulation frequency agrees very well although the actual power penalties measured for $f_1 = 100$ MHz have been higher [14] giving a nearly modulation frequency-independent offset in comparison with the calculation. This discrepancy is mainly attributed to the imperfect modulation of the DQPSK signal states resulting from the use of a simple phase modulator in the DQPSK transmitter leading to additional phase distortions. For DPSK, an offset penalty was not observed. For modulation frequencies below 100 MHz (not shown here), the measured penalty is also growing due to SBS-induced distortions. Comparing Figs. 2 and 5 show that the modulation frequency has to be chosen to about twice the Brillouin bandwidth in order to have a reasonable tradeoff between good SBS suppression and low-induced OSNR penalty. In conclusion, the OSNR penalty induced by the pump-phase modulation is a major source of degradation especially for DQPSK signals. Using a dual-tone scheme with low maximal modulation frequency can improve the OSNR penalty slightly.

### D. Experimental Setup

The experimental setup for the characterization of the wavelength converter as well as for the system experiments is shown in Fig. 6. The AOWC comprised one optical path for the signal and one for the CW pump. The polarization state and optical power of both were controlled independently to optimize the conversion process. The signal pulses were injected into 1100 m of dispersion-shifted HNLF (the parameters are given in Table I) through the weak arm of a 10 dB coupler, with a power of about 3 dBm at the HNLF input. A CW pump [external cavity laser (ECL)] at 1548 nm was phase-modulated with a sinusoidal modulation function, which was varied in frequency (between 50 and 1000 MHz) and in maximum phase shift (between 1 and 2.5 rad) to suppress SBS. The pump power was coupled into the HNLF through the 10 dB coupler’s strong arm with a power of +11 to +20 dBm at the HNLF input. An optical isolator blocked the reflected power from a tunable fiber Bragg grating (FBG) that was used as a notch filter to suppress the 1548 nm pump. An additional optical bandpass filter (3 dB width of 5 nm) suppressed the 1553 nm input signal, allowing only the converted signal at 1542.5 nm to pass. For the characterization of the AOWC, a 80–320 Gbit/s DQPSK transmitter [14] was used, consisting of a 10 GHz tunable mode-locked laser (TMLL, 1.6 ps pulselength) followed by a phase stabilized 4× pulse multiplier and data encoding by a two-stage phase modulation (PRBS $2^7 - 1$) to create 80 Gbit/s DQPSK data signals,

---

**Fig. 4.** Experimentally measured (solid symbols) and calculated (open symbols) average ER as function of the modulation frequency for the single-tone scheme with modulation index $m_1 = 2$ rad. For the experiment, unmodulated 40 GHz pulses have been used as input signal. The theoretical curve has been obtained using (8) with $\phi_0 = 0.32$ rad.
which were subsequently multiplexed (MUX) up to 320 Gbit/s (160 Gbd symbol rate). The pattern length was considered to be sufficient because of the negligible dispersion, and thus, almost no interactions between adjacent bits. The optically preamplified receiver comprised a clock recovery, a demultiplexer, a delay-line interferometer (DLI), and a bit error rate tester (BERT).

V. CASCADIBILITY

Since signals generally pass through several nodes in optical networks, it will be necessary for wavelength converters to be cascaded without imposing severe degradation on the signal. The question of cascadibility is addressed in this section. We will investigate how the phase distortion induced by the pump-phase modulation and the resulting OSNR penalty develops for several wavelength conversions. Let us first assume a signal passing two identical wavelength converters inducing the same phase distortion, e.g., within a single node. With the use of (3), its envelope is given by

$$A_2(t) = \sqrt{P_{in}(t)} \eta g \times \exp \left[ i \left( 2 \phi_P(t) - 2 \phi_S(t) + \frac{\pi}{2} \right) \right]$$

$$= \sqrt{P_{in}(t)} \eta g \exp (i \phi_S(t)).$$

We see that, in principle, the pump-phase contributions \(\phi_P\) of the subsequent AOWCs can cancel out each other keeping an undistorted data signal phase. However, in this case, the sinusoidal phase modulation signals must be synchronized by a phase-locked loop to keep up a constant phase relation between them. In a general case, with the AOWCs separated by hundreds of kilometers, we have to assume that the pump-phase
contributions of different AOWCs are distributed randomly. Let us assume a signal that has passed \( N \) wavelength converters with identical conversion efficiency \( \eta_C \) but different pump-phase contributions \( \phi_{P,n} \):

\[
A_N(t) = \sqrt{P_m(t)} \eta_C^N \exp \left[ i \left( (1)^N \phi_s(t) 
+ \sum_{n=1}^{N} (-1)^{n+1} \left( 2\phi_{P,n}(t) + \pi \right) \right) \right].
\]

(11)

We see that the pump-phase contributions simply add in the signal phase. For simplicity, we will now refer only to the single-tone scheme. With (5), the explicit form of \( \phi_{P,n}(t) \) is given by (\( m_2 = 0 \))

\[
\phi_{P,n}(t) = m_1 \cos (2\pi f_1 t + \theta_n)
\]

(12)

with the randomly distributed phases of the modulation functions \( \theta_n \). The overall pump phase contribution can then be written as

\[
\Phi_{P,N}(t) = 2 \sum_{n=1}^{N} (-1)^{n+1} \phi_{P,n}(t)
\]

\[
= 2m_1 \sum_{n=1}^{N} (-1)^{n+1} \cos (2\pi f_1 t + \theta_n)
\]

\[
= 2m_1 \Re \left\{ \sum_{n=1}^{N} (-1)^{n+1} \exp (2\pi i f_1 t) \exp (i \theta_n) \right\}
\]

\[
= 2m_1 \cos (2\pi f_1 t + \xi) \sum_{n=1}^{N} (-1)^{n+1} \exp (i \theta_n).
\]

The last factor acts as a multiplier for the modulation index \( m_1 \) and will be called \( m' \), and \( \xi \) accounts for the sum’s complex phase. We assume that the \( \theta_n \) are distributed uniformly in the interval \([0, 2\pi]\). The best case is given by \( m_{BC} = 0 \) for \( \theta_1 = \theta_2 = \cdots = \theta_n \) and the worst case is given by \( m_{WC} = N \) for \( |\theta_1| = |\theta_2| = \cdots = |\theta_n| \) but alternating signs.

In this paper, we want to restrict ourselves to the worst case. In Fig. 7, the OSNR penalties for DPSK and DQPSK, both for \( \Delta \phi_0 = 0.32 \) rad, \( f_1 = 100 \) MHz, and different modulation indices \( m_1 \), are shown. The previous results indicate that forward-error correction (FEC) will be needed in systems with cascaded conversions. Therefore, the penalties are now taken at a BER of \( 10^{-3} \) representing the target BER for FEC. That is why the penalties shown in Fig. 7 for a single conversion are lower than in Fig. 5. Nevertheless, they very quickly increase with the number of conversions. From (6), it is clear that the OSNR penalty will decrease with decreasing \( m_1 \). For ten conversions of DPSK signals, the difference between the curves corresponding to \( m_1 = 1 \) rad and \( m_1 = 2.5 \) rad is about 4 dB. However, since the modulation index also determines the conversion efficiency as seen in Fig. 3, we have to pay for the penalty reduction with a decrease in FWM efficiency. Therefore, a careful compromise for the modulation index \( m_1 \) has to be found depending on the position of the AOWC and the number of the conversions. Generally, the penalties obtained for DPSK signals are within a reasonable range for more than ten conversions.

In Fig. 7, the OSNR penalties for DQPSK are also shown. The tendencies are the same as for DPSK, but the magnitude of the penalties is generally higher. This is due to the smaller Euclidian distance of the signal states that results in a higher sensitivity to phase distortions compared to DPSK.

VI. CONCLUSION

In this paper, we have theoretically and experimentally investigated the impact of the pump-phase modulation in fiber-based parametric wavelength converters on DPSK and DQPSK signals. Different common modulation schemes have been investigated. The investigation of multifrequency schemes shows that the modulation frequencies have to be chosen in the order of the Brillouin bandwidth making the use of many modulation tones ineffective. Quantitative results for signals with a line rate of 40 GBd have been given for single- and dual-tone schemes and single and multiple conversions, respectively. In particular, it was shown that the pump-phase modulation used to suppress SBS introduces critical signal degradations and OSNR penalties on DPSK signals, and much more on DQPSK signals.

REFERENCES


Robert Elschner (S’06) was born in Eisenhüttenstadt, Germany, in 1979. He received the Dipl.-Ing. degree in electrical engineering in 2006 from the Technical University of Berlin, Berlin, Germany, where he is currently working toward the Ph.D. degree at the Institut für Hochfrequenztechnik und Halbleiter-Systemtechnik, Technical University of Berlin, in the field of all optical wavelength conversion and regeneration. During 2005, he was with the Ecole Nationale Supérieure des Télécommunications, Paris, France, in research on all-optical clock recovery using high-speed fiber devices.

Christian-Alexander Bunge (S’01–A’02–M’03) was born in Berlin, Germany, in 1973. He received the Dipl.-Ing. degree in electrical engineering from the Technical University of Berlin, Berlin, in 1999. During 1999–2002, he was with the Institut für Hochfrequenztechnik und Halbleiter-Systemtechnik, Technical University of Berlin, as a Research Associate, where he was engaged in research on multimode fiber transmission for 10 Gb/s Ethernet. From 2002 to 2004, he was with the Polymer Optical Fiber (POF) Application Center, Nuremberg, Germany, as a Senior Scientist responsible for POF modeling. Since 2004, he has been with the Technical University of Berlin, where he is engaged in research on optical transmission systems, all-optical signal processing, and modeling of optical components.

Authorized licensed use limited to: Technische Universitaet Berlin. Downloaded on April 27, 2009 at 08:29 from IEEE Xplore. Restrictions apply.
Reinhold Ludwig was born in Lahnstein, Germany, in 1952. He received the Ing. Grad. degree from the Fachhochschule Koblenz, Koblenz, Germany, in 1974, and the Dipl. Ing. and Dr. Ing. degrees from the Technical University of Berlin, Berlin, Germany, in 1985 and 1993, respectively.

In 1985, he joined the Heinrich Hertz Institute (HHI), Berlin, where he is engaged in research on photonic components and systems. He was a Visiting Scientist at Nippon Telephone and Telegraph Company (NTT), Japan, in 1991, and at Bell Laboratories in 1993. Since 1985, he has been the author or coauthor of more than 300 scientific papers in the fields of high-speed optical transmission and all-optical signal processing. He is the holder of several patents. In 1996, he founded the first HHI spin-off company (LKF Advanced Optics GmbH) and served as CEO until the merger of LKF and i2t Innovative Optoelectronic Components GmbH in 2001.

Dr. Ludwig is a member of the Verband Der Elektrotechnik Elektronik Informationstechnik (VDE). He is the recipient of the Philip Morris Research Award in 1999, and was nominated for the Innovation Award of the German Bundespräsidient.

Bernd Hüttl was born in Berlin, Germany, in 1961. He received the Diplom-Physiker and Ph.D. (Dr. rer. nat.) degrees in physics from the Humboldt University, Berlin, in 1988 and 1997, respectively.

In 1988, he joined the Academy of Sciences of the German Democratic Republic, Berlin, to develop dye lasers emitting ultrashort pulses. Since 1992, he has been a member of the Scientific Staff at the Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut, Berlin. His current research interests include the development of flat electroluminescence displays, semiconductor mode-locked lasers, and high-speed transmission systems.

Carsten Schmidt-Langhorst was born in Berlin, Germany, in 1972. He received the Diploma (Dipl.-Phys.) and Ph.D. (Dr. rer. nat.) degrees in physics from the Technical University of Berlin, Berlin, Germany, in 1997 and 2004, respectively.

Since 1998, he has been with the Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut, Berlin. His current research interests include transmission, all-optical processing, and detection of optical data signals at a picosecond time scale, and in particular, all-optical sampling techniques. Furthermore, he is currently engaged in several projects in the field of ultrafast optical transmission technology.

Dr. Schmidt-Langhorst is the recipient of the Philip Morris Research Award in 1999. He is a member of the Deutsche Physikalische Gesellschaft (DPG) and the Association for Electrical, Electronic and Information Technologies (VDE).

Colja Schubert was born in Berlin, Germany, in 1973. He received the Dipl.-Phys. and Dr. rer. nat. degrees in physics from the Technische Universität Berlin, Berlin, in 1998 and 2004, respectively.

From 1996 to 1997, he was an exchange student at the Strathclyde University, Glasgow, U.K. During 1997–1998, he was with the Max-Born-Institute for Nonlinear Optics and Short Pulse Spectroscopy, Berlin. Since 2000, he has been a member of the Scientific Staff at the Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut, Berlin, where he is engaged in research on high-speed transmission systems and all-optical signal processing and is coheading the “High-Speed Transmission” Group in the Photonic Networks and Systems Department.

Dr. Schubert is a member of the German Physical Society.

Klaus Petermann (M’76–SM’85) was born in Mannheim, Germany, on October 2, 1951. He received the Dipl.-Ing. and Dr. Ing. degrees from the Technische Universität Braunschweig, Braunschweig, Germany, in 1974 and 1976, respectively, all in electrical engineering.

From 1974 to 1976, he was a Research Associate at the Institut für Hochfrequenztechnik, Technische Universität Braunschweig, where he was engaged in research on optical waveguide theory. From 1977 to 1983, he was with AEG-Telefunken, Forschungsinstitut Ulm, Germany, where he was engaged in research on semiconductor lasers, optical fibers, and optical fiber sensors. In 1983, he became a Full Professor at the Technische Universität Berlin, Berlin, Germany. His current research interests include optical fiber communications and integrated optics.

Prof. Petermann is a member of the Senate of the Deutsche Forschungsgemeinschaft (German research council) and Berlin–Brandenburg Academy of Science. He is the recipient of the Leibniz Award from the “Deutsche Forschungsgemeinschaft” in 1993, and the “Distinguished Lecturer” Award from the Laser and Electro-Optics Society within the IEEE in 1999/2000. From 1999 to 2004, he was an Associate Editor of the IEEE PHOTONICS TECHNOLOGY LETTERS. From 1996 to 2004, he was a member of the board of the Verband Der Elektrotechnik Elektronik Informationstechnik (VDE). From 2004 to 2006, he was the Vice President for research at the Technische Universität Berlin.