Novel Nonmagnetic 30-dB Traveling-Wave Single-Sideband Optical Isolator Integrated in III/V Material

Suhas Bhandare, *Member, IEEE*, Selwan K. Ibrahim, David Sandel, Hongbin Zhang, Frank Wüst, and Reinhold Noé, *Member, IEEE*

***Abstract*—Various attempts have been made to fabricate waveguide-type isolators in III/V material by implanting magnetic materials, but none of them has so far resulted in a commercial product. Here, we report for first time on an integrated optical isolator implemented in III/V material. It consists of a single-sideband electrooptic modulator where traveling electrical waves make the transmission direction-dependent. Isolation is 30 dB, excess insertion loss is 8 dB. Residual rms ripple is 7% for peak-to-peak RF driving amplitudes of 3.5 V at 4.0 GHz. The estimated transmission penalty for 40 Gb/s return-to-zero differential phase shift keying (RZ-DPSK) signals is 0.2 dB (0 dB measured).**

***Index Terms*—Integrated optical devices, optical isolator, traveling-wave (TW) devices.**

I. Introduction

PROGRESS in optical communication systems requires a higher level of integration of different types of functional optical elements. Most of these could be implemented in III/V material. This integration definitely needs laser sources and integrated optical amplifiers to compensate for losses. Optical isolators are essential for such integration because they protect laser diodes and semiconductor optical amplifiers from unwanted reflections and are, therefore, necessary to ensure source stability, especially when fast switching speeds and large bandwidths are required. Standard optical isolators are based on the Faraday effect. Several attempts have been made to fabricate waveguide-type optical isolators using magnetic garnet films grown on oxide substrates [1]–[4]. Others [5]–[7] are integrated approaches based on the use of metallic ferromagnetic films or composites. In all mentioned isolators—see also [8]—a static magnetic field is required to break the symmetry (reciprocity) between the two propagation directions. None of these attempts has resulted in a commercial waveguide product so far.

Here, we present a nonmagnetic optical isolator that can be easily integrated as a part of larger optoelectronic integrated circuits (OEICs) in III/V material. Other than in [1]–[8], traveling waves (TWs) consisting of electrical ac signals are needed to break the symmetry between the propagation directions. The core idea behind this novel device is that the TWs make the transmission in a single-sideband electrooptic modulator direction-dependent and thereby configure it to behave as an optical isolator.

Manuscript received June 29, 2004; revised November 20, 2004.

The authors are with the Chair for Optical Communication and High-Frequency Engineering, the University of Paderborn, 33098 Paderborn, Germany (e-mail: noe@upb.de; suhas@ont.upb.de).

Digital Object Identifier 10.1109/JSTQE.2005.845620

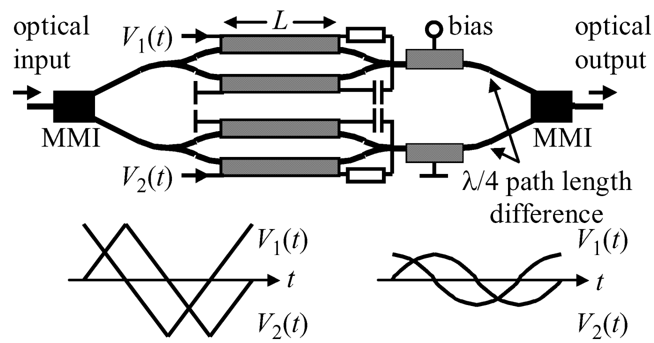


Fig. 1. Traveling-wave single-sideband (TW-SSB) isolator and corresponding driving voltages.

II. Principle of Operation

The single-sideband electrooptic modulator shown in Fig. 1 contains two TW Mach–Zehnder modulators with electrode length L. These two modulators are placed in the two arms of another interferometer that forms a Mach–Zehnder superstructure. Multimode interference (MMI) couplers are used at input and output of the device but any other symmetric couplers/splitters may work just as fine. This superstructure has quadrature control electrodes in both arms for active phase control.

The two sets of TW electrodes are ac terminated with 50 Ω. Application of additional dc bias voltages allows these two modulators to be biased for minimum transmission. RF modulation voltages $V_1(t)$, $V_2(t)$, where t is the time, are used to generate mean experienced differential phase shifts $2\Delta\varphi_{1,\pm}(t)$, $2\Delta\varphi_{2,\pm}(t)$ between the two waveguides of a modulator. The optical field transfer functions of the two modulators are, therefore, proportional to $\sin\Delta\varphi_{1,\pm}(t)$ and $\sin\Delta\varphi_{2,\pm}(t)$. The $+$ and $-$ signs denote co- and counter-propagation, respectively, of optical waves and electrical waves in the TW electrodes. For $i = 1, 2$, the expression

$$\Delta\varphi_{i,\pm}(t) = g \int_{z=0}^{L} e^{-\alpha_e z} V_i \times \left(t - \frac{c_o^{-1} L (1 \pm 1)}{2} + \left(\pm c_o^{-1} - c_e^{-1} \right) z \right) dz$$

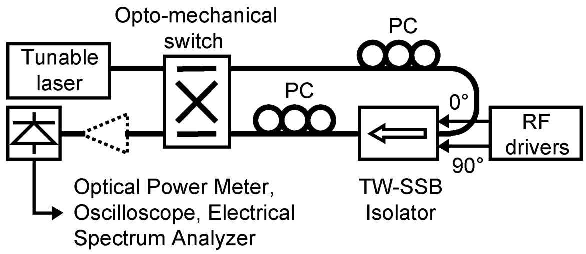


Fig. 2. Characterization setup of GaAs/AlGaAs TW-SSB isolator.

holds, where g is a constant and α_e is the electrical attenuation coefficient of the TW electrodes. The mean experienced phase shifts also depend on applied voltages, electrical and optical propagation velocities c_e, c_o and the relative propagation sense.

The optical field transfer function of the whole superstructure can be written as $H_\pm = (1/2)(\sin \Delta\varphi_{1,\pm}(t) + j \sin \Delta\varphi_{2,\pm}(t))$. If the sign of the 90° optical phase shift is changed then the sign of the imaginary term becomes opposite. If electrical attenuation is negligible, i.e., $\alpha_e = 0$, then the modulator has a large bandwidth. We assume zero loss and velocity matching, $c_o = c_e$. Therefore, the modulator ideally has an infinite bandwidth for copropagation.

Ideally, triangular modulation voltages $V_i(t)$ of frequency F are chosen, with a quarter period delay with respect to each other (as shown in Fig. 1, bottom left). The amplitude is chosen so that the peak amplitudes of $\Delta\varphi_{i,+}(t)$ equal $\pm\pi/2$. The transfer function in copropagation mode is, therefore, $H_+ = (1/2)e^{j2\pi Ft}$. There is an intrinsic loss of 6 dB, and an optical frequency shift by F.

Let $F = m/(L(c_o^{-1} + c_e^{-1}))$ with a nonzero integer m. As a result, the mean experienced differential phase shift in the counter-propagation mode equals zero, $\Delta\varphi_{i,-} = 0$. As a consequence, the optical field transfer function of the superstructure becomes $H_- = 0$. Such direction-dependent transmission describes an optical isolator. We call it a TW single sideband (TW-SSB) isolator.

Even if velocity matching is not perfect, the driving voltages can still be chosen so that H_+ describes a pure frequency shift, but the intrinsic propagation loss will be increased beyond 6 dB. With the same effect, sinusoidal driving voltages (as shown in Fig. 1, bottom right) can be used, with small amplitudes to avoid unwanted output intensity modulation. As long as electrical attenuation is negligible, perfect isolation is always possible.

III. Characterization

Fig. 2 shows the characterization setup of the TW-SSB isolator. The optical signal with 1550-nm wavelength from an external cavity tunable laser source was directed either in forward or in backward direction with an input power of +7 dBm through a pigtailed Bookham GaAs–AlGaAs TW differential quadrature phase shift keying (DQPSK) modulator [9], using an optomechanical 2 × 2 switch. Sinusoidal driving voltages with a mutual phase difference of 90° were applied at both TW inputs. The polarization controllers before and after the TW-SSB isolator were adjusted for maximum transmission in both propagation directions, thereby ensuring equal polarizations in both cases. This step is important because the nonreciprocal properties need to be determined, not the polarizing properties. No matter what the bias and driving voltages were, one polarization was strongly suppressed (∼37 dB) in the device, probably due to a built-in polarizer. The isolator is polarization-dependent, like almost all electrooptic modulators.

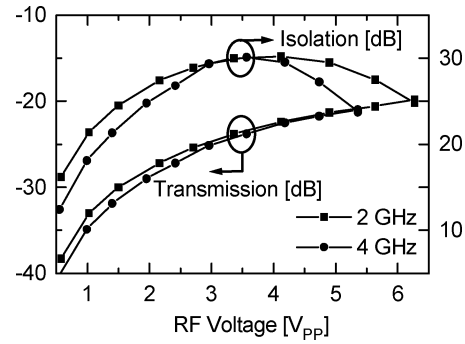


Fig. 3. Forward fiber-to-fiber insertion loss and isolation versus RF driving amplitudes.

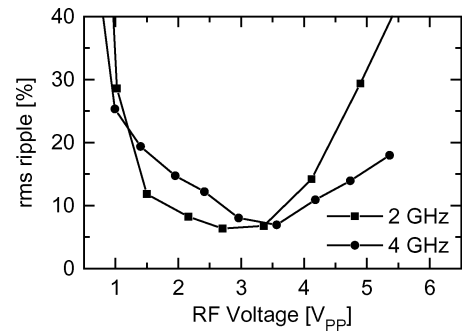


Fig. 4. Residual rms ripple versus RF driving amplitudes.

The interaction length L is 24 mm. The optimum driving frequency F was found to be 2.0 GHz $(m = 1)$ or 4.0 GHz $(m = 2)$, with very similar device performance. The output of the TW-SSB isolator was connected to an optical power meter or via an EDFA to a 50-GHz photodiode. Its output signal was directed to an oscilloscope (26.5-GHz bandwidth) or to an electrical spectrum analyzer (40-GHz bandwidth).

Measured forward fiber-to-fiber insertion loss and isolation (= forward minus backward transmission) in dB are shown in Fig. 3 as a function of peak-to-peak RF driving amplitudes. The associated residual rms ripple is shown in Fig. 4. Performance is best for peak-to-peak voltages of 3.5 V: Forward fiber-to-fiber insertion loss is 23.8 dB, and isolation is 30 dB, both at 2.0 and 4.0 GHz. The corresponding backward loss is 53.8 dB.

Without RF and when all modulator bias voltages were optimized for maximum transmission, the forward/backward insertion loss 15.8 dB. So, the total forward transmission loss (23.8 dB) of the TW-SSB isolator consists of fiber coupling and semiconductor propagation losses (together 15.8 dB) and an 8-dB excess loss. The excess loss is somewhat higher than the intrinsic 6-dB loss of an ideal TW-SSB isolator with triangular driving voltages.

Isolator performance was identical for electrical phase shifts of ±90°.

Higher frequencies were also tried out but the isolation was decreased to 25.5, 20, and 14 dB at 6.0, 8.0, and 10.0 GHz,

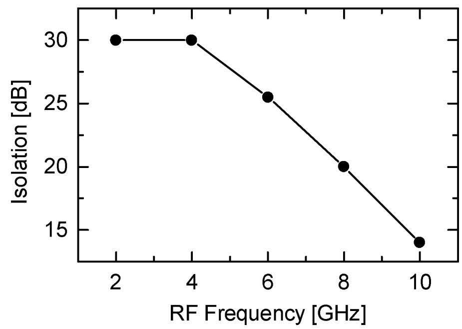


Fig. 5. Isolation versus drive frequency $(m = 1, 2, \ldots, 5)$.

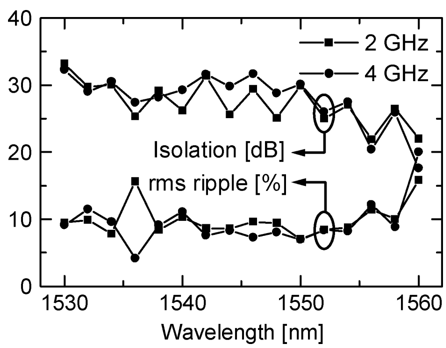


Fig. 6. Isolation and rms ripple versus wavelength over C band.

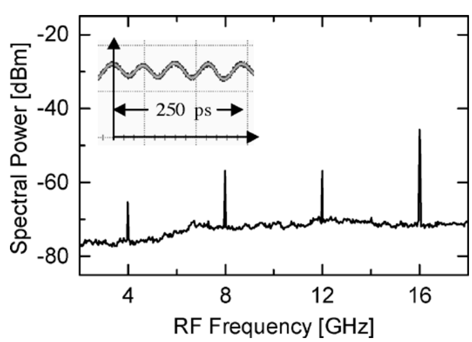


Fig. 7. Output RF spectrum and ac ripple (inset) in one period of the 4-GHz driving signal (resolution bandwidth: 5 MHz) at 1550 nm.

respectively (see Fig. 5). The reduced performance can be explained by a nonnegligible electrical attenuation at high frequencies.

At 1550-nm wavelength, the rms ripple is 7% under the optimized operating conditions which were determined during the detailed characterization of the TW-SSB isolator. Fig. 6 shows isolation and rms ripple in percent as a function of wavelength in the C band for fixed operating conditions (optimized at 1550-nm wavelength). The recorded RF spectrum and the oscillogram in Fig. 7 shows that the residual ripple is dominated by the fourth harmonic of the modulating RF signals. This indicates that peaked driving voltages (similar to triangles) could further reduce the ripple.

IV. Transmission Experiment

The penalty of the TW-SSB integrated optical isolator was evaluated by inserting it into a 40-Gb/s return-to-zero DPSK

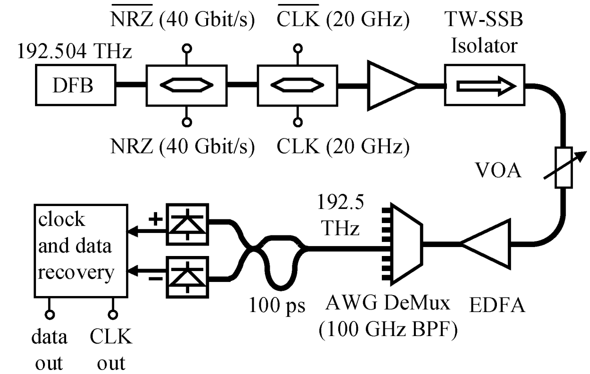


Fig. 8. RZ-DPSK transmission penalty measurement setup with TW-SSB isolator.

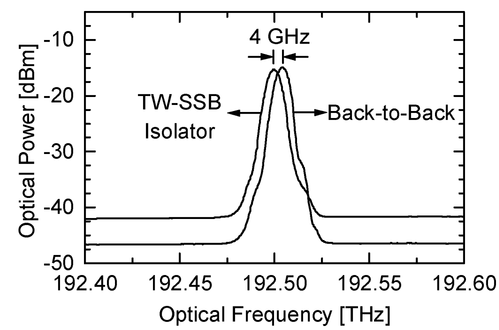


Fig. 9. Back-to-back and the down-shifted frequency spectrum of the TW-SSB isolator at 192.5 THz (resolution bandwidth: 10 GHz).

(RZ -DPSK) transmission setup as shown in Fig. 8. The transmitter employs a 16 : 1 Infineon multiplexer that processes 16 2.5 Gb/s data streams, mutually delayed by multiples of 8 b to generate 40-Gb/s nonreturn to zero (NRZ) data for modulation. The modulator drivers from SHF communication technology drive a Triquint dual-drive modulator. Another Triquint dual drive pulse carver driven at half the clock rate generates the RZ-DPSK signal for transmission. The transmitter uses a distributed feedback (DFB) laser diode at 192.5 THz as a source.

At the receiver input there are optical preamplifiers and a flat-top C-band dense wavelength division multiplexing (DWDM) DEMUX (Optun) that is used as a narrow optical bandpass filter. A temperature-stabilized integrated-optical Mach-Zehnder interferometer with a delay of four symbol durations is used as a delay demodulator. For proper reception of DPSK signals, the phase difference of delay demodulator is set to 0° using differential micro-heaters with total constant power. The demodulator outputs are connected to two high-speed photodetectors from $\mathrm{u^2t}$, which in turn are connected to the differential inputs of a 1 : 16 Infineon demultiplexer with clock and data recovery. A $2^7 - 1$ pseudorandom bit sequence (PRBS) was transmitted.

A variable optical attenuator allows to evaluate the receiver sensitivity. The DFB laser was thermally tuned to 192.504 THz. The TW-SSB isolator shifted the frequency down by 4 GHz to make the signal pass through the 192.5-THz channel of the AWG. The receiver sensitivity was −31.9 dBm. The frequency shift is seen in the optical spectrum of Fig. 9. Modulation was switched off during this measurement to improve the visibility of the frequency shift.

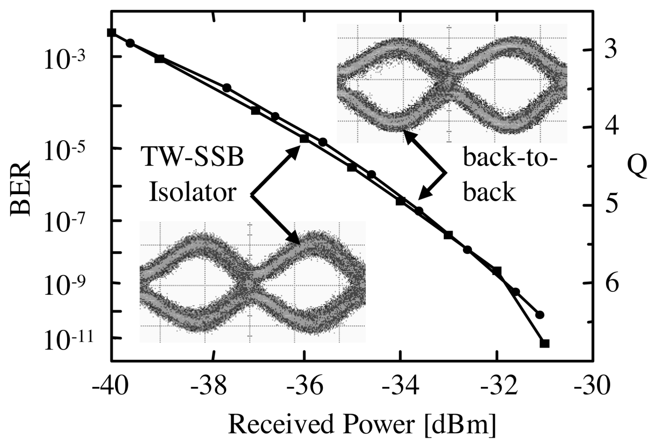


Fig. 10. Receiver sensitivity for 40-Gb/s RZ-DPSK transmission experiments, back-to-back and through TW-SSB isolator with corresponding eye diagrams.

Fig. 10 shows measured bit-error rate (BER) versus received optical power at the optical preamplifier input expressed in decibels with respect to 1mW (dBm) for back-to-back configuration and with the TW-SSB isolator in place. Probably due to a DPSK modulator drift, the back-to-back sensitivity measured with a laser frequency of 192.5 THz was not better than with TW-SSB isolator. The experiment was repeated, with the same result. The true TW-SSB isolator penalty was therefore estimated from the rms ripple. It is about 0.2 dB for DPSK signals. The eye diagram was only slightly affected by the TW-SSB isolator as can be seen in Fig. 10.

V. Discussion

If some light passes directly between the two MMI couplers of Fig. 1, then the setting of the various bias voltages for minimum ripple in forward direction may differ from the setting for optimum isolation. The finite isolation may be partly due to this effect.

The forward insertion loss is strongly influenced by the fiber-to-chip coupling. The on-chip insertion loss is presently >8 dB but can be lowered by triangular signals. Yet, it is a weak point of the isolator. When such isolators are suitably integrated on III/V OEICs with semiconductor optical amplifiers, then the insertion loss should be tolerable, given that the gain of each amplifier easily exceeds 20 dB. Of course, TW-SSB isolators make sense only where the benefits of optical integration are large and can only be achieved with on-chip isolation.

In this context, note that a CS-RZ Mach-Zehnder pulse carver can also isolate the continuous wave (CW) source from reflections which occur after the TW modulator, if the electrode length is properly chosen. In that special case isolation comes for free.

The backward suppression (isolation) of a TW-SSB isolator can of course be switched off by setting $F = 0$. In practice the traveling electrical waves must be turned off and (at least) one of the modulators is rebiased for maximum transmission.

Note that in principle, no polarizers are needed in order to suppress the unwanted (orthogonal) polarization. This is because the wave with the unwanted polarization will not be modulated, and both MZ modulators will be biased at the point of minimum transmission, unless the birefringence is not the same in all waveguides. Polarization-independent operation probably requires a polarization diversity scheme, with polarization splitters and mode converters.

It is of course attractive to integrate the RF drivers together with the modulators on the same chip. For sinusoidal driving, an inductive–capacitive (LC) resonant power oscillator can drive two Mach–Zehnder modulators, and the required phase shift between the modulator driving signals can be established by a delay line. Alternatively, ring oscillators can include the TW electrodes (in series, or in parallel with mutual phase shifts) and on-chip delay lines in the ring. Ring oscillators reduce the power consumption, and intrinsically operate at the correct frequency. For oscillation in a higher than the fundamental ring mode (as required by the large ring delay) the lower ones must be suppressed by LC (or stub) filtering.

If the optical frequency shift is not tolerable in a DWDM environment, then two TW-SSB isolators can be cascaded. One shifts the frequency up, the other shifts it back down, and isolation (in decibels) should double. Depending on the phase shift between sinusoidal driving voltages of the two different isolators the ripple could also be reduced.

A conventional optical isolator has a limited bandwidth whereas the TW-SSB isolator can, in principle, have a very large optical bandwidth; this requires all optical path lengths to be made exactly equal. Also, all Y-forks and one of the MMI couplers must be replaced by wavelength-flattened 3-dB couplers which provide 90° phase shifts.

VI. Conclusion

A GaAs–AlGaAs DQPSK modulator has been operated as a TW single-sideband integrated optical isolator. The isolation is $\sim$30 dB and the excess insertion loss is $\sim$8 dB. The signal transmission penalty is 0 dB measured (0.2 dB calculated) for 40 Gb/s RZ-DPSK signals. The device can become a basic building block of larger III/V OEICs, especially with integrated semiconductor optical amplifiers.

Acknowledgment

The authors would like to thank Dr. R. Griffin (Bookham) for the loan of the DQPSK modulator.

References

[1] N. Sugimoto, H. Terui, A. Tate, Z. Katoh, Z. Zamada, A. Sugita, A. Shibukawa, and Z. Inoue, "A hybrid integrated waveguide isolator on a silica-based planner lightwave circuit," *IEEE J. Lightw. Technol.*, vol. 14, no. 11, pp. 2537–2546, Nov. 1996.

[2] O. Zhuromsky, H. Dötsch, M. Lohmeyer, L. Wilkens, and P. Hertel, "Magnetooptical waveguides with polarization-independent nonreciprocal phaseshift," *IEEE J. Lightw. Technol.*, vol. 19, no. 2, pp. 214–221, Feb. 2001.

[3] M. Levy, H. C. Yang, M. J. Steel, and J. Fujita, "Flat-top response in one-dimensional magnetic photonic bandgap structures with faraday rotation enhancement," *IEEE J. Lightw. Technol.*, vol. 19, no. 12, pp. 1964–1969, Dec. 2001.

[4] T. Izuhara, J. Fujita, M. Levy, and R. M. Osgood, "Integration of magnetooptical waveguides onto a III-V semiconductor surface," *IEEE Photon. Technol. Lett.*, vol. 14, no. 2, pp. 167–169, Feb. 2002.

[5] W. Zaets and K. Ando, "Optical waveguide isolator based on nonreciprocal loss/gain amplifier covered by ferromagnetic layer," *IEEE Photon. Technol. Lett.*, vol. 11, no. 8, pp. 1012–1015, Aug. 1999.

[6] J. M. Hammer, J. H. Abeles, and D. J. Channin, "Polycrystalline-metal-ferromagnetic optical waveguide isolator (POWI) for monolithic-integration with diode-laser devices," *IEEE Photon. Technol. Lett.*, vol. 9, no. 5, pp. 631–633, May 1997.

[7] J. M. Hammer, G. A. Evans, G. Ozgur, and J. K. Butler, "Isolator, polarizers and other optical-waveguide devices using a resonant-layer effect," *IEEE. J. Lightw. Technol.*, vol. 22, no. 7, pp. 1754–1763, Jul. 2004.

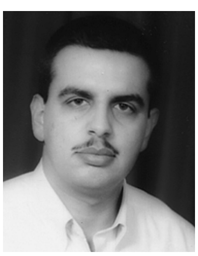
[8] M. Levy, "The on-chip integration of magnetooptic waveguide isolators," *IEEE J. Sel. Topics Quantum Electron.*, vol. 8, no. 6, pp. 1300–1306, Nov./Dec. 2002.

[9] R. A. Griffin and A. C. Carter, "Optical differential quadrature phase-shift key (oDQPSK) for high capacity optical transmission," in *Proc. Optical Fiber Conf.*, 2002, WX6, pp. 367–368.

Suhas Bhandare (M'05) was born in Nashik, India, in 1973. He received the Master's degree in science and philosophy, in an area of electronic science, from the University of Pune, Pune, India in 1995 and 1999, respectively, and the Ph.D. degree (Dr.-Ing.) in electrical engineering on the application of lithium niobate based integrated optical circuits to optical communication from the University of Paderborn, Paderborn, Germany, in 2003.

He was a Core Member of the team that has established the Design and Engineering Center for Integrated Optics at the Society for Applied Microwave Electronics Engineering and Research, Indian Institute of Technology Powai, Mumbai, India. At this Center, he has spent three years on the design, fabrication, and characterization of various types of integrated optical devices based on glass and lithium niobate. In 1999, he joined the Chair for Optical Communication and High-Frequency Engineering, the University of Paderborn, Germany, as a Research Assistant. His research interests include phase shift keying transmission at 40 Gb/s.

Dr. Bhandare is a life member of IETE.



Selwan K. Ibrahim was born in 1977. He received the B.Sc. and M.Sc. degrees in electronics and communications engineering from the University of Baghdad, Baghdad, Iraq, in 1999 and 2002, respectively. He is currently working toward the Ph.D. (Dr.-Ing.) degree at the University of Paderborn, Paderborn, Germany.

In 2002, he joined the Chair for Optical Communication and High-Frequency Engineering, the University of Paderborn.

David Sandel was born in Wangen/Allgäu, Germany, on December 26, 1966. He received the Dipl.-Ing. degree from the Technische Hochschule Karlsruhe, Karlsruhe, Germany, in 1992, and the Dr.-Ing. degree on fiber Bragg gratings from the University of Paderborn, Paderborn, Germany. In 1997.

In 1992, he joined the Chair for Optical Communications and High-Frequency Engineering, the University of Paderborn. His research interests include polarization dispersion compensation and polarization multiplex data transmission.

Hongbin Zhang received the Ph.D. degree in physical electronics and optoelectronics from University of Electronic Science and Technology of China, Chengdu, in June 1999.

From July 1999 to May 2001, he was a Postdoctor/Associate Professor with the National Key Laboratory of Optical Fiber Communication, University of Electronic Science and Technology of China. From June 2001 to December 2003, he was a Postdoctor with the Optical Interconnection Technology (OIT) Group, Cooperative Computing and Communication Laboratory (C-LAB), which is a joint institute of the University of Paderborn, Paderborn, Germany, and Siemens AG. Since January 2004, he has been with the Optical Communication and High-Frequency Engineering, University of Paderborn. His current research interests include optical interconnect technologies, laser sources, and optical fiber communication technology.

Frank Wüst was born in Siegen, Germany, in 1967. He received the diploma and Ph.D. degrees in electrical engineering from the University of Karlsruhe (TH), Karlsruhe, Germany, in 1994 and 1999, respectively.

While he was with the University of Karlsruhe, he worked on band structure engineering, optical gain, and alpha-factor of strained MQW-InAlGaAs/InP high frequency lasers. Since 1999, when he joined the Chair of Optical Communication and High-Frequency Engineering, University of Paderborn, Paderborn, Germany, he has been engaged in the research and development of polarization division multiplex. His current research interests include photonic devices and electronic devices on the nano scale.

Reinhold Noé (M'93) was born in Darmstadt, Germany, in 1960. He received the Dipl.-Ing. and Dr.-Ing. degrees in electrical engineering from Technische Universität München, Munich, Germany, in 1984 and 1987, respectively. At that time, he realized the first endless polarization control systems.

He then spent a Postdoctoral year at Bellcore, Red Bank, NJ, to continue his work on coherent optical systems. In 1988, he joined Siemens Research Laboratories, Munich. Since 1992, he has been heading the Chair of Optical Communication and High-Frequency Engineering at the University of Paderborn, Paderborn, Germany. He has (co)authored more than 140 publications and is one of the Editors of *Electrical Engineering*. Most of his recent experiments deal with PMD detection and compensation, polarization division multiplex, chromatic dispersion detection, and phase shift keyed transmission, at 40. . .160 Gbit/s per DWDM channel.

Prof. Noé is a frequent referee for IEEE publications and *Electronics Letters*.