Novel Non-Magnetic, 30-dB Optical Isolator Integrated in III/V Material

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Abstract *Traveling electrical waves define a direction-dependent transmission in a single-sideband electrooptic modulator. Isolation is 30dB, excess loss is 8dB, and transmission penalty for a 40Gbit/s RZ-DPSK signal is 0.3dB calculated (0dB measured).*

Introduction

Any advanced optical signal processing in III/V materials, based on more than a very small scale optical integration, will require integrated optical amplifiers and therefore also optical isolators. Various attempts have been made to implant magnetic materials into integrated optics [1-6], but none of them seems to have resulted in a commercial product so far. Here we present a novel optical isolator, integrated in III/V material. It does not require any magnetic material or field. Rather, traveling electrical waves define a direction-dependent transmission in a single-sideband electrooptic modulator.

Operation principle

A single-sideband optical modulator (Fig. 1) consists of two traveling-wave Mach-Zehnder modulators with electrode lengths L sitting one each in the two arms of another Mach-Zehnder interferometer. The two sets of traveling wave electrodes are AC-terminated. Application of additional bias voltages allows to bias each of the modulators at the point of zero intensity. RF voltages modulation voltages $V_1(t)$, $V_2(t)$ generate mean experienced differential phase shifts $2\varphi_{1,\pm}(t)$, $2\varphi_{2,\pm}(t)$ and give the two modulators optical field transfer functions $\sin\varphi_{1,\pm}(t)$, $\sin\varphi_{2,\pm}(t)$, respectively. The + and – signs denote co- and counterpropagation, respectively, of optical and electrical waves. For i = 1,2 the expression

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

where g is a constant describes mean experienced phase shifts depending on applied voltages, optical and electrical propagation velocities c_o, c_e, and relative propagation sense.

The rightmost set of electrodes allows the outer Mach-Zehnder structure to be biased with a 90° phase shift between its arms. The whole structure has an optical field transfer function $H_\pm = (1/2)\left(\sin\varphi_{1,\pm}(t) + j\sin\varphi_{2,\pm}(t)\right)$. The sign of the imaginary term becomes opposite if the sign of the 90° phase shift is changed.

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

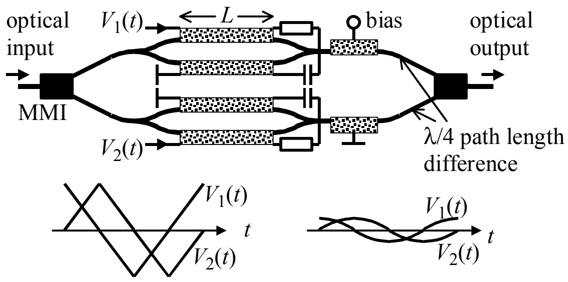

Fig. 1: Traveling-wave single-sideband modulator and isolator, and its drive voltages for operation at an intrinsic forward loss of 6 dB (left) or higher (right)

Let $F = m/\left(L\left(c_o^{-1} + c_e^{-1}\right)\right)$ with a non-zero, integer m. As a result, the mean experienced phase shifts in counterpropagation mode equal zero, $\varphi_{i,-}(t) = 0$. Hence the conterpropagation transfer function equals zero, $H_- = 0$. This behavior describes an isolator.

If velocity matching is not perfect the driving waveforms can still be chosen so that H_+ describes a pure frequency shift, but the intrinsic copropagation loss will increase beyond 6 dB. With the same effect, sinusoidal driving voltages (bottom right in Fig. 1) can be used, with small amplitudes to avoid unwanted output intensity modulation. Perfect isolation is always possible if the traveling wave losses are negligible.

Experiment

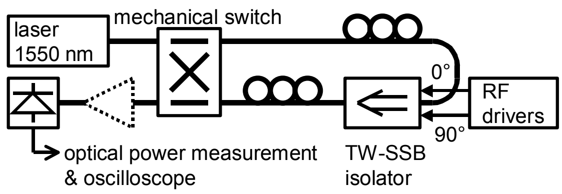

Fig. 2: Characterization of GaAs/AlGaAs traveling-wave single-sideband (TW-SSB) isolator

1550-nm DFB laser light (Fig. 2) was directed with a power of +7 dBm either in forward or in backward direction through a Bookham GaAs/AlGaAs traveling-wave DQPSK modulator [7], which is similar to Fig. 1 top. Sinusoidal drive signals with a mutual phase difference of 90° were applied at the traveling wave inputs. The polarization controllers were adjusted for maximum transmission, thereby ensuring equal polarizations in both propagation directions. The drive frequency was either 2.0 GHz (m = 1) or 4.0 GHz (m = 2), with similar performance. Either a power meter, or an EDFA followed by a 45 GHz photodiode and a 26 GHz oscilloscope were connected at the output. Forward fiber-to-fiber transmission, isolation (= forward minus backward transmission in dB), and rms ripple of output power (unwanted intensity modulation) are shown in Fig. 3 as a function of drive amplitude. Values of –23.8 dB, > 30 dB (calculated from a measured backward loss > 53.8 dB) and 7% dB, respectively, were obtained for 3.3 V_{pp} at 2 GHz, and for 4 V_{pp} at 4 GHz. Without RF and when all bias voltages were optimized the transmission was 8 dB better, i.e. –15.8 dB. Isolator performance was identical for electrical phase shifts of ±90°.

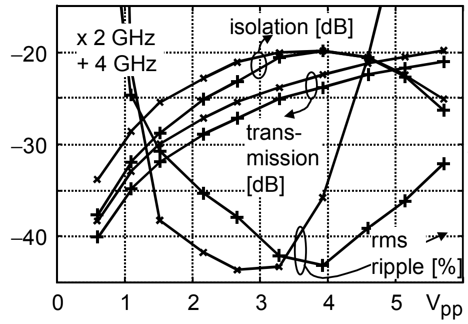

Fig. 3: Foward fiber-to-fiber insertion loss, isolation and rms ripple vs. driving amplitude

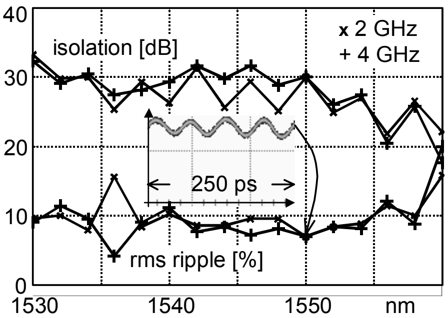

Fig. 4: Isolation and ripple vs. wavelength. Inset: output ripple in one period of the 4 GHz driving signal

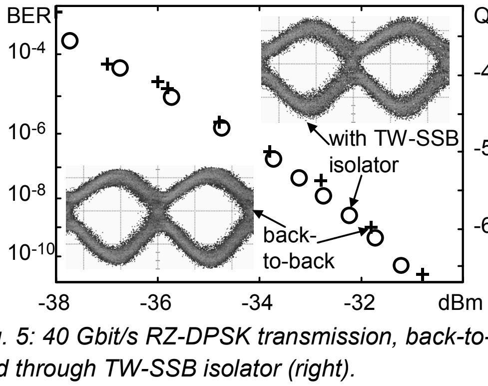

Fig. 5: 40 Gbit/s RZ-DPSK transmission, back-to-back and through TW-SSB isolator (right).

Higher frequencies were also tried but isolation decreased to 25.5, 20 and 14 dB at 6, 8 and 10 GHz, respectively. Fig. 4 shows isolation and peak-to-peak ripple as a function of wavelength for fixed operating conditions. The ripple is dominated by the 4th harmonic (inset). This indicates that peaked driving voltages could reduce the ripple.

Finally, a 40-Gbit/s RZ-DPSK signal with a laser frequency of 192.504 THz was passed through the TW-SSB isolator. It shifted the frequency down by 4 GHz to match a subsequent AWG. The receiver sensitivity was –31.9 dBm (Fig. 5). Probably due to modulator drift the back-to-back sensitivity, measured with a laser frequency of 192.5 THz, was no better. The true isolator penalty was therefore calculated from the rms ripple; it is about 0.3 dB. The eye diagram was only slightly affected by the isolator.

Discussion

The finite isolation may be partly owed to the following: If some light passes directly between the two MMI couplers in Fig. 1 then the various bias points must be changed to maintain minimum ripple.

The forward insertion loss is strongly influenced by fiber-to-chip coupling. When the isolator is suitably integrated on a III/V OEIC with semiconductor optical amplifiers the added loss will be tolerable.

If the optical frequency shift is too large in a DWDM environment then two cascaded isolators can be implemented, where an up- and a downshift of the optical frequency result in a vanishing total shift and probably a much reduced ripple.

Conventional optical isolators have limited bandwidth. The TW-SSB isolator can in principle have a very large optical bandwidth, if all path lengths are made exactly equal and if the Y forks of the modulators and one of the MMI couplers are replaced by wavelength-flattened 3-dB couplers to provide 90° phase shifts.

Conclusion

A traveling-wave single-sideband isolator has been realized, using a GaAs/AlGaAs DQPSK modulator. Isolation is ~30 dB, excess loss is ~8 dB and signal transmission penalty is ~0.3 dB. The device is expected to be useful as a building block of larger III/V OEICs with semiconductor optical amplifiers.

Acknowledgement

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