# All-optical extinction-ratio enhancement of a 160 GHz pulse train by a saturable-absorber vertical microcavity

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A vertical-access passive all-optical gate has been used to improve the extinction ratio of a 160 GHz picosecond pulse train at 1555 nm. An extinction ratio enhancement of 6 dB is observed within an 8 nm bandwidth. Such a device is a promising candidate for low-cost all optical reamplication and reshaping (2R) regeneration at 160 Gbits/s. © 2006 Optical Society of America

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Expanding existing transmission links based on standard optical fiber to higher bit rates, typically 160 Gbits/s, is an attractive method to reduce the number of wavelength channels and the global complexity of the system for the same capacity. In such future networks, overcoming the propagation impairments will require ultrahigh-speed regenerators. Because of the increasing complexity of optoelectronic devices with increasing bit rate and of their speed limitations, all-optical devices are attractive for low-cost in-line signal processing.[1,2] These devices need a nonlinear intensity transfer function (output power versus input power) to enable them to perform their role as nonlinear gates. In this context, such gates, based on saturable absorbers (SAs), have generated considerable interest in all-optical switching in particular, owing to their large nonlinear optical effect, their compactness, and their fully passive operating mode (no bias voltage, no Peltier cooler) and thus potential low cost. For these SA-based gates the nonlinear transfer function is achieved by modulation of the carrier density in the active region. To amplify the nonlinear response and to reduce the switching energy, SAs are placed inside an asymmetric Fabry–Perot microcavity. The use of microcavity effects combined with excitonic absorption enhances the effective nonlinearity and thus contributes to the reduction of switching energy.[3] Furthermore, the SA microcavity device is used at normal incidence, thus yielding intrinsic polarization-insensitive operation. To significantly decrease the response time of these materials, capture and recombination centers can be introduced during or after crystal growth by means of low-temperature molecular beam epitaxy,[4] high-energy ion implantation,[5] or Be or Fe doping.[6,7] These methods of damage creation have been reported to provide recovery times as short as a few picoseconds in an InP-based semiconductor.[5] The combination of heavy-ion irradiation with a silver-based backmirror compact microcavity has proved to be a convenient solution to making efficient optical gates.[8] The benefits of quantum-well microcavity saturable absorbers in a 40 Gbit/s long-haul transmission demonstration that used a 5 ps relaxation-time component have already been reported.[9]

In this Letter we investigate the extinction-ratio enhancement capabilities at 160 GHz of a quantum-well microcavity SA device with a picosecond pulse train source at 1555 nm. Autocorrelation function and frequency-resolved optical gating (FROG) measurements, adapted for high-repetition-rate periodic pulse trains,[10,11] were used to characterize the intensity and the phase of the 160 GHz processed signal.

The device structure shown schematically in Fig. 1 is similar to those reported elsewhere.[12,13] The active layer consists of $7\times$InGaAs/InP multiple quantum wells (QWs) grown by metal-organic vapor-phase epitaxy upon an InP substrate and contained in a microcavity. The multiple quantum wells are suitably located at the antinodes of intracavity intensity. After

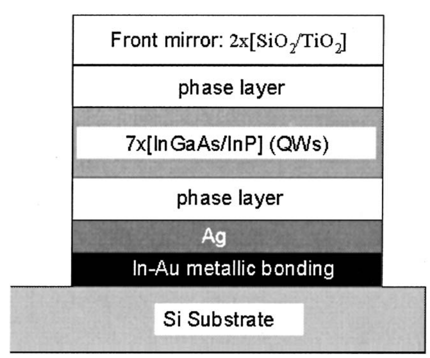


Fig. 1. Structure of the device.

 

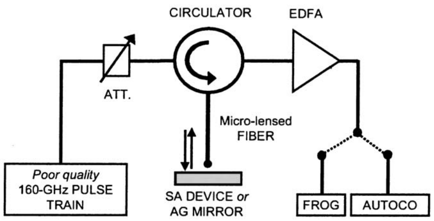


Fig. 2. Experimental setup: Att. attenuator; EDFA, erbium-doped fiber amplifier; AUTOCO, autocorrelation.

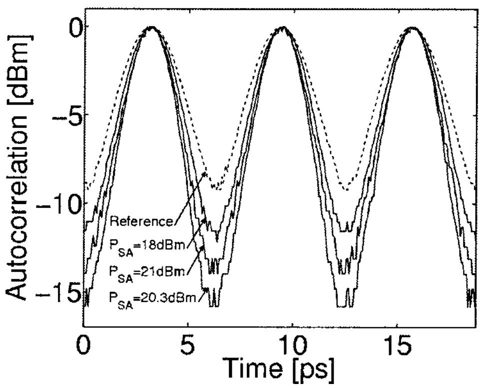


Fig. 3. Autocorrelation traces of the 160 GHz pulse train as functions of SA input average power; dashed curve, the Ag mirror reference.

the growth of the semiconductor layers, the structure underwent 12 MeV $Ni^{6+}$ ion irradiation at a dose of $1\times10^{12}\ cm^{-2}$. Such energetic ions create clusters of defects along the ion path through the active layer. These defects act as carrier recombination centers, which reduce the carrier lifetime from a few nanoseconds to a few picoseconds.[14] Pump and probe measurement at 1555 nm showed a response time of only 1 ps. The backmirror was made by deposition of a thin silver layer. Top-down mounting bonded this Ag film onto a silicon wafer by an indium gold isothermal solid–liquid interdiffusion technique[15] that facilitates heat dissipation. Finely controlled chemical etching of the InP phase layers permitted a resonance adjustment within the telecommunication wavelength window, which is also the multiple quantum-well excitonic absorption wavelength range. Finally, a two-period dielectric layer ($2\times SiO_2/TiO_2:\lambda/4\ \lambda/4$) was deposited as the microcavity's front mirror. This cavity was designed to have a reflectivity close to zero at low intensity (impedance matching) and has a typical −3 dB bandwidth of 50 nm.

The experimental setup is shown in Fig. 2. First a high-quality 160 GHz picosecond pulse train was generated at 1555 nm by a multiple four-wave mixing technique in a 1 ps/nm/km, 1 km long nonzero dispersion-shifted fiber.[16] Then, to test the regeneration efficiency of our SA device, we degraded the generated pulse train by increasing the average power to 900 mW at the nonzero dispersion-shifted fiber input. The resultant poor-quality 160 GHz pulse train was then focused onto a Ag mirror by a microlens optical fiber to record a reference autocorrelation trace (dashed curve in Fig. 3). We also checked its power independence in the same range of power as in the SA experiment described below. The Ag mirror was then substituted for the microcavity SA device. The shift in resonance wavelength owing to thermal effects was previously compensated for, as described elsewhere.[13]

Figure 3 shows an autocorrelation trace of the 160 GHz pulse train at the SA output as a function of input average power ($P_{SA}$). We can clearly observe a large enhancement of the autocorrelation contrast as the input power is increased, and a maximum improvement of 6.6 dB occurs for an optimum input average power ($P_{SA}$opt) of 20.3 dBm.

The 160 GHz pulse trains, the Ag mirror reference, and the 20.3 dBm SA signal were also characterized in intensity and phase by means of a background-free second-harmonic-generation FROG setup.[16] Figure 4 shows the FROG results: We can clearly see a large improvement in the pulse quality after reflection on the SA device, especially on the pulse wings, where extinction ratio enhancements of 6 and 2 dB are observed, confirming the absorption saturation role of the device. We can also see that the phase remains nearly unchanged between the two measurements, indicating that no nonlinear phase distortion is experienced by the pulses. Finally, we can observe that the pulses become asymmetric after the SA device. Although the second-harmonic-generation FROG trace is symmetric and consequently leaves ambiguity in the direction of time,[17] we could attribute this phenomenon to the finite relaxation time of the SA, which leads to a saturation of the device on the falling edge and prevents efficient wing absorption.

To complete the characterization of our SA device, finally we tested its spectral bandwidth and suitability to be used in a wavelength-division multiplexing environment. For a range of wavelength from 1550 to 1558 nm we made the same study as described in Fig. 3, and we show in Fig. 5 the best autocorrelation contrast enhancement as well as the corresponding optimum input average power ($P_{SA}$opt) as a function of wavelength. Figure 5 shows that a constant extinction-ratio enhancement near 6 dB is achieved within an 8 nm bandwidth while the optimum input average power stays relatively constant near 20 dBm. We may note that a higher extinction ratio

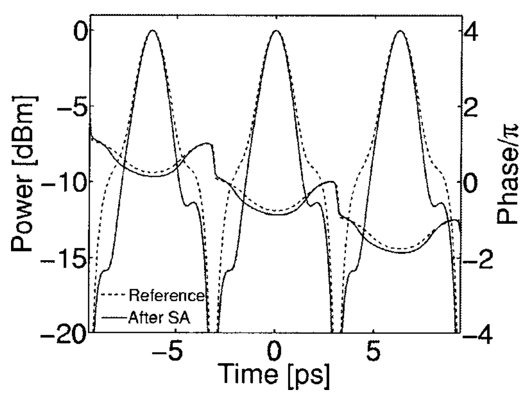


Fig. 4. FROG results. Intensity profile and phase of the 160 GHz pulse train at the SA input: Ag mirror reference and after the SA output for an average input power of 20.3 dBm.

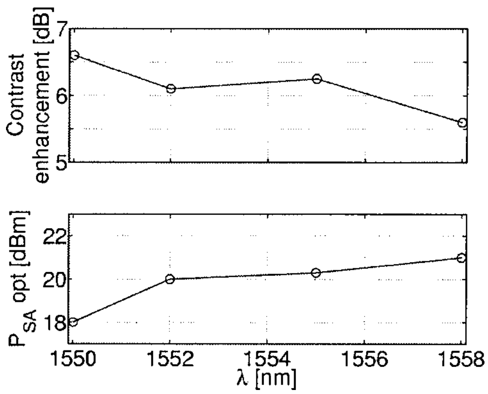


Fig. 5. Top, autocorrelation extinction-ratio enhancement as a function of wavelength. Bottom, optimum SA input average power as a function of wavelength.

would cause the signal quality to deteriorate (spectral broadening owing to temporal compression); thus a switching contrast of 6 dB is sufficient to enhance wavelength-division multiplexed long-haul transmissions.[9] We also note that for a return-to-zero modulated signal at 160 Gbits/s with a pulse duration similar to that in the present study, the optimum average power would be reduced by 3 dB for the same peak power, as the signal would contain 50% (on average) symbol 0 bits that make essentially no contribution to the average power.

In summary, we have investigated the extinction-ratio enhancement capabilities at 160 GHz of an all-optical gate based on a quantum-well microcavity saturable absorber. A 160 GHz picosecond pulse train was generated by multiple four-wave mixing at 1555 nm and used for the measurements. Autocorrelation trace and frequency-resolved optical gating measurements show that an extinction-ratio enhancement of 6 dB is achieved within an 8-nm bandwidth for an optimum input average power of ~20 dBm. This device is thus a promising candidate for low-cost, all-optical reamplication and reshaping (2R) regeneration at 160 Gbits/s.

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## References

1. D. Cotter, J. K. Lucek, and D. D. Marcenec, IEEE Commun. Mag. **35**, 90 (1997).
2. O. Leclerc, presented at 11th European Conference on Integrated Optics, Prague, April 2–4, 2003.
3. J. L. Oudar, R. Kuszelewicz, B. Sfez, J. C. Michel, and R. Planel, Opt. Quantum Electron. **24**, S193 (1993).
4. R. Takahashi, Y. Kawamura, T. Kagawa, and H. Iwamura, Appl. Phys. Lett. **65**, 1790 (1994).
5. E. L. Delpon, J. L. Oudar, N. Bouche, R. Raj, A. Shen, N. Stelmakh, and J. M. Lourtioz, Appl. Phys. Lett. **72**, 759 (1998).
6. L. Qian, S. D. Benjamin, P. W. E. Smith, B. J. Robinson, and D. A. Thompson, Appl. Phys. Lett. **71**, 1513 (1997).
7. M. Guezo, S. Loualiche, J. Even, A. L. Corre, O. Dehaese, Y. Pellan, and A. Marceaux, J. Appl. Phys. **94**, 2355 (2003).
8. J. Mangeney, G. Aubin, J. L. Oudar, J. C. Harmand, G. Patriarche, H. Choumane, N. Stelmakh, and J. M. Lourtioz, Electron. Lett. **36**, 1486 (2000).
9. D. Rouvillain, P. Brindel, F. Seguineau, L. Pierre, O. Leclerc, H. Choumane, G. Aubin, and J. L. Oudar, Electron. Lett. **38**, 1113 (2002).
10. F. Gutty, S. Pitois, P. Grelu, G. Millot, M. D. Thomson, and J. M. Dudley, Opt. Lett. **24**, 1389 (1999).
11. J. M. Dudley, F. Gutty, S. Pitois, and G. Millot, IEEE J. Quantum Electron. **37**, 587 (2001).
12. D. Massoubre, J. L. Oudar, H. Choumane, G. Aubin, J. C. Harmand, A. Shen, J. Decobert, J. Landreau, and B. Thdrez, presented at Integrated Photonics Research, San Francisco, June 30–July 2, 2004.
13. D. Massoubre, J. L. Oudar, G. Aubin, J. Dion, A. Shen, J. Decobert, N. Lagay, A. O'Hare, Z. Belfqih, M. Gay, L. Bramerie, S. Seve, E. Lecren, and J. C. Simon, presented at Conference on Lasers and Electo-optics, Baltimore, Md., 2005.
14. J. Mangeney, H. Choumane, G. Patriarche, G. Leroux, G. Aubin, J. C. Harmand, and J. L. Oudar, Appl. Phys. Lett. **79**, 2722 (2001).
15. C. C. Lee, C. Y. Wang, and G. Matijasevic, IEEE Trans. Compon., Hybrids, Manuf. Technol. **16**, 311 (1993).
16. S. Pitois, J. Fatome, and G. Millot, Opt. Lett. **27**, 1729 (2002).
17. R. Trebino, *Frequency-Resolved Optical Gating: the Measurement of Ultrashort Laser Pulses* (Kluwer Academic, 2000).