Integrated Tandem Traveling-Wave Electroabsorption Modulators for >100 Gbit/s OTDM Applications

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***Abstract*—Integrated tandem traveling-wave electroabsorption modulators are demonstrated as high-speed optical short pulse generators and demultiplexers for >100 Gbit/s optical time-division-multiplexed systems. The tandem significantly increases the extinction ratio and further compresses the optical pulses in comparison to a single modulator. An extinction ratio of ∼50 dB is achieved while optical pulses of 4–6 ps width at 30–40 GHz are generated.**

***Index Terms*—Demultiplexing, electroabsorption, optical fiber communication, optical switches, traveling wave devices.**

I. Introduction

OPTICAL fiber transmission based on single channel optical time-division multiplexing (OTDM) has recently attracted a lot of attention as a means of upgrading future TDM systems [1]–[3]. Due to advances in high-speed electrical TDM, it is inevitable that next generation OTDM systems will operate at a base rate of 40 Gbit/s with optical multiplexing to 160 Gbit/s or more [4]. For high-speed OTDM systems, sinusoidally driven electroabsorption (EA) modulators have become key devices as optical short pulse generators and optical demultiplexers. An 80 Gbit/s OTDM data stream (with 10 Gbit/s base rate) was realized by short pulses generated from EA modulators without using any nonlinear pulse compression, which is the highest aggregate data rate achieved using this technique to date [5]. On the other hand, a 160 Gbit/s optically multiplexed data stream was demultiplexed to 10 Gbit/s using only EA modulators [1].

Single EA modulators are usually limited to ∼20 dB dynamic extinction ratio, which is sufficient for demultiplexing purposes, but can lead to incoherent interference between multiplexed adjacent pulses in OTDM transmitters [2]. Therefore, a fiber-coupled pair of separate modulators was used for pulse generation in [5] and for demultiplexing in [1]. This configuration not only effectively doubles the dynamic extinction ratio, but also reduces the switching window. However, it is desirable to integrate the tandem on a single chip in order to eliminate the external optical amplifier, which compensates for the coupling losses between the modulators [6], [7]. This results in a compact and cost-effective transmitter (or demultiplexer) as well as an environmentally robust module.

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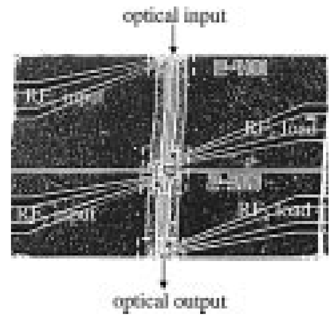

Fig. 1. Photograph of the integrated tandem traveling-wave EA modulators (dashed areas are the ion-implanted regions).

In this letter, we investigate the optical short pulse generation and demultiplexing capability of integrated tandem traveling-wave EA modulators at repetition frequencies of 30 GHz and 40 GHz for >100 Gbit/s OTDM systems. This is also the first demonstration of optical pulse generation using traveling-wave EA modulators, which were previously demonstrated in a 30 Gbit/s data modulation experiment [8].

II. Device Characteristics

The EA modulators used for the OTDM application were based on a traveling-wave electrode structure fabricated with MOCVD grown ten periods of strain-compensated InGaAsP quantum wells on semi-insulating InP substrate [9]. Traveling-wave EA modulators have the advantage of overcoming the RC limitation (in comparison to lumped EA modulators) resulting in longer devices with higher bandwidths and increased extinction ratios. The 2-μm wide, 300-μm and 400-μm long EA modulators were cleaved as a tandem (Fig. 1). The 20-μm long optical waveguide between the two modulators was defined by H^+ ion implantation and the measured impedance was 50 kΩ. The ion implantation also extended 50 μm into each modulator in order to reduce capacitance and microwave crosstalk (<-30 dB); however, the absorption region for each modulator was shortened by 100 μm. Both modulators were terminated in a thin-film resistor and a dielectric capacitor, which reduced heating effects and allowed for long-term operation of the tandem without any external temperature cooling.

Fig. 2 shows the transmission characteristics of the tandem as a function of reverse bias. An optical input power of 7 dBm was applied at 1555 nm. The insertion loss of the tandem was 14.1 dB and 15.3 dB for the TE and TM polarizations, respectively. Each device was individually characterized by keeping

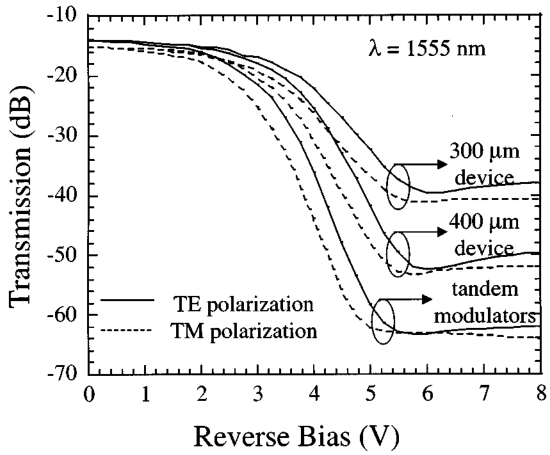

Fig. 2. Fiber-to-fiber transmission versus reverse bias voltage for the integrated tandem EA modulators. Solid: TE polarization. Dashed: TM polarization.

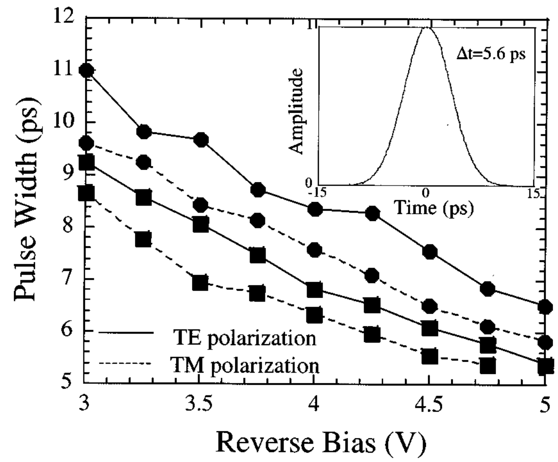

Fig. 3. Pulsewidth as a function of reverse bias at 30 GHz modulation for the individual devices. Circle symbols: 300-μm device; Square symbols: 400-μm device. Inset: Autocorrelation trace of the 5.6 ps pulse generated by the 400-μm device at a reverse bias of -4.5 V.

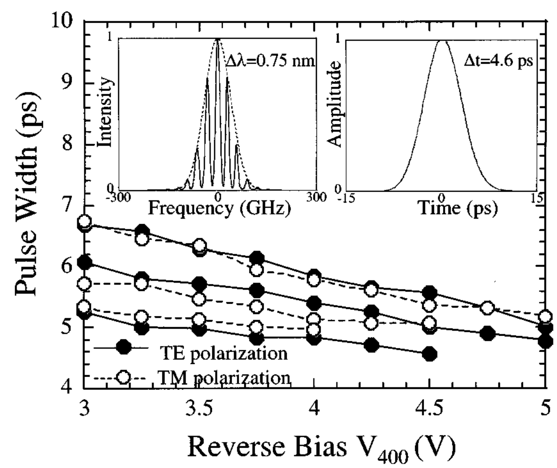

Fig. 4. Pulsewidth as a function of 400-μm reverse bias and for several 300-μm biases (top-to-bottom) at 30 GHz modulation. Closed symbols: TE polarization (top-to-bottom: -3.5 V, -4 V, -4.5 V); Open symbols: TM polarization (top-to-bottom: -3 V, -3.5 V, -4 V). Left inset: Optical spectrum; Right inset: Autocorrelation trace of the 4.6 ps pulse.

the other modulator at zero bias. The 400-μm device achieved a maximum extinction of 38 dB at -6 V while 26 dB of extinction was observed for the 300-μm device. The difference in the maximum extinction ratios is due to the shorter absorption region of the 300-μm device. It should also be noted that at high reverse biases, a saturation of absorption due to the quantum well excitonic peak is observed for both devices. Even though it is desirable to apply a high reverse bias in order to generate short switching windows using sinusoidal modulation, the absorption saturation will deteriorate the extinction ratio and generate significant wings [10]. These wings are detrimental for OTDM applications since the resulting incoherent interference in the transmitter and the crosstalk in the receiver will significantly degrade system performance. On the other hand, the tandem configuration shows an improved extinction ratio of ~50 dB while the absorption saturation is well suppressed in comparison to single device operation. A 14-dB reduction in the total expected extinction is observed, which is attributed to higher-order mode coupling.

III. Experimental Results and Discussion

The optical switching capability of the tandem was first characterized at 30 GHz. Both modulators were driven with $7V_{pp}$ sinusoidal RF signals, which were synchronized by an electrical delay line. The widths of the optical pulses were measured using a second harmonic generation autocorrelator and deconvolved assuming a gaussian pulse shape as inferred from the optical spectrum measurements. It is important to mention that the following criteria were used for these measurements: 1) the average optical output power was higher than -25 dBm in order to ensure a high signal-to-noise ratio (SNR), and 2) the dynamic extinction ratio was estimated to be >20 dB. The pulsewidths obtained from the individual devices by keeping the other device at zero bias are shown in Fig. 3. At a reverse bias of -4.5 V, a minimum pulsewidth of 6.5 ps and 5.6 ps were obtained for the 300- and 400-μm devices, respectively. Even though shorter pulses were achieved at higher reverse biases, degradation in the dynamic extinction ratio was observed due to the absorption saturation as discussed in the preceding section.

Fig. 4 shows the obtained pulsewidths as a function of reverse biases for the tandem configuration. A minimum pulsewidth of 4.6 ps (inset to Fig. 4) with a fiber-coupled output power of -24.2 dBm was achieved while an average of 5–6 ps pulses were observed over a wide range of reverse biases and polarization states. This switching window is well suited for >100 Gbit/s optical demultiplexing applications [2]. The inset to Fig. 4 also shows the optical spectrum of the modulated tandem of EA modulators, which has a gaussian shape of 0.75 nm. The time-bandwidth product of 0.43 suggests that the pulses were slightly chirped. When the tandem was followed by dispersion-compensating fiber (DCF) with a dispersion of about -6 ps/nm, the pulses were linearly compressed to a transform-limited pulsewidth of 4.2 ps (Fig. 5). This pulsewidth suggests that the tandem is suitable as an optical pulse source for simultaneous polarization- and TDM systems in excess of 100 Gbit/s.

The optical switching response of the tandem EA modulators was also performed at 40 GHz with RF drives of $7V_{pp}$. The frequency response of the devices was estimated to be ~4 dB lower

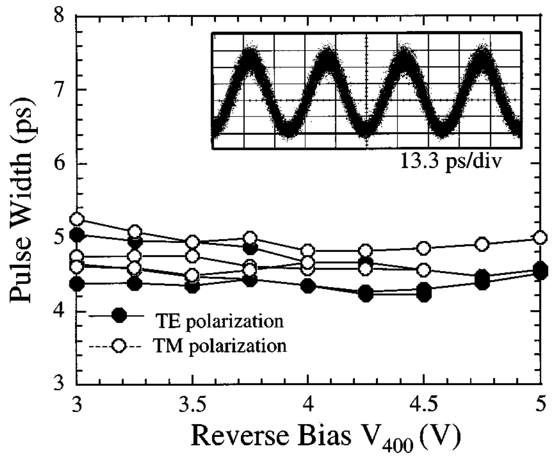

Fig. 5. Pulsewidth as a function of 400-μm reverse bias and for several 300-μm biases (top-to-bottom) at 30 GHz modulation (tandem device followed by dispersion-compensating fiber). Closed symbols: TE polarization (top-to-bottom: -3.5 V, -4 V, -4.5 V); Open symbols: TM polarization (top-to-bottom: -3 V, -3.5 V, -4 V). Inset: Oscilloscope trace of the 30 GHz pulses (13.3 ps/div).

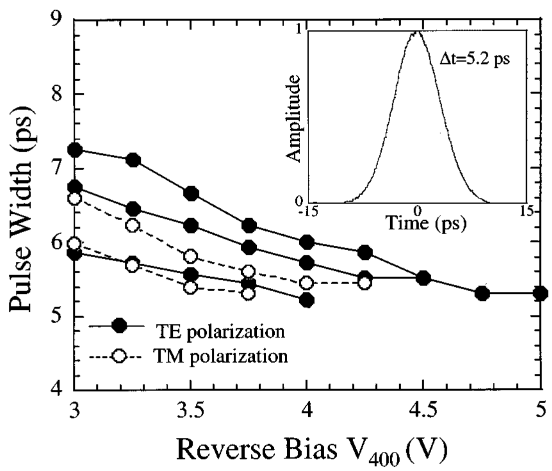

Fig. 6. Pulsewidth as a function of 400-μm reverse bias and for several 300-μm biases (top-to-bottom) at 40 GHz modulation. Closed symbols: TE polarization (top-to-bottom: -3 V, -3.5 V, -4 V); Open symbols: TM polarization (top-to-bottom: -3 V, -3.5 V). Inset: Autocorrelation trace of the 5.2 ps pulse.

at 40 GHz (in comparison to the 30 GHz response), which resulted in a compromise between pulsewidth, dynamic extinction ratio and average optical output power. A minimum optical pulsewidth of 5.2 ps with an optical bandwidth of 0.59 nm was achieved (Fig. 5). These results should improve when the tandem is driven with higher power RF amplifiers at 40 GHz and enable low-penalty optical demultiplexing of 160 Gbit/s OTDM data stream to 40 Gbit/s [2].

IV. Conclusion

In summary, we have successfully demonstrated integrated tandem traveling-wave EA modulators for $>$100 Gbit/s OTDM applications. Optical pulses of 4 to 6 ps width were obtained with high extinction ratio, high optical input power, and high average optical output power. These devices are a viable technology for optical demultiplexing of bit rates up to 160 Gbit/s.

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