1.31-to-1.55 μm Wavelength Conversion by Optically Pumping a Distributed Feedback Amplifier

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***Abstract*—We demonstrate a new technique for all-optical wavelength conversion to 1.55 μm by using a 1.3-μm signal that directly pumps a distributed feedback semiconductor optical amplifier. Data polarity can be selected by tuning the probe wavelength to different regions of the Bragg resonance. Polarity-inverted signals exhibit a digital-like transfer function with an on–off ratio of 4 and 2.4 at 155.5 and 622 Mb/s, respectively. This simple wavelength-conversion scheme is insensitive to the direction and polarization of the 1.31-μm signal, and should be affordable for local access and other cost-sensitive optical-network layers.**

***Index Terms*—All optical, digital response, distributed feedback, semiconductor optical amplifiers, wavelength conversion.**

I. INTRODUCTION

THE CAPACITY of optical communication systems can be increased by simultaneously using both low–loss spectral windows of silica fiber located near 1310 and 1550 nm. Data signals of either window can be discriminated using low-cost demultiplexers, making such a wavelength-division multiplexing (WDM) scheme affordable even for cost-sensitive, local-access applications [1]. In addition to demultiplexing, all-optical wavelength conversion (i.e., data transfer) between the 1310-nm and 1550-nm spectral windows would be a critical technology because its use enhances flexibility at optical cross-connects and add/drop multiplexing nodes. For use in local-access systems, wavelength converters must be inexpensive while retaining high performance.

Many of the 1310-to-1550 wavelength converters demonstrated previously perform well, but they are expensive. Instead of high-cost components like $LiNbO_3$ waveguides [2], semiconductor optical amplifiers (SOA's) are often employed. However, SOA-based wavelength converters using interferometric cross-phase modulation [1] and nonlinear loop mirrors [3] will require expensive control schemes to realize conversion over a large input-power dynamic range. A more affordable wavelength converter was demonstrated using a split-contact, Fabry–Perot SOA [4]. Data transfer occurs within such a device as the 1310-nm signal saturates an absorber section and changes the gain experienced by a 1550-nm probe beam.

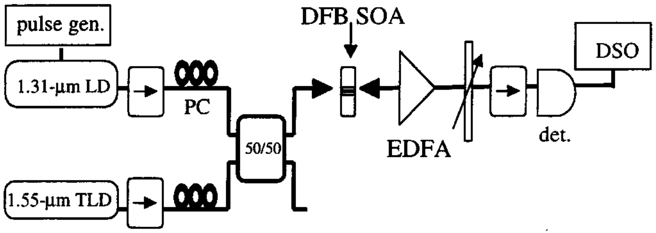

Fig. 1. Experimental system. Transmission of a CW, 1.5-μm probe beam through the DFB SOA is modulated by a 1.3-μm data signal.

We demonstrate wavelength conversion using a single-contact, distributed feedback (DFB) SOA. Our device is simply a commercial DFB laser driven below lasing threshold. Absorption of a 1310-nm signal generates charge carriers within the device's active region, thereby increasing its gain and decreasing its refractive index. These gain-*pump*-induced changes are reverse of those occurring for gain-*saturation*-induced cross-gain modulation (XGM) [5] and cross-phase modulation (XPM) [6] conversion techniques. Thus, in a similar fashion, optical gain-pumping signals transfer their data by controlling the transmission of a 1550-nm probe beam.

II. EXPERIMENT

Our experimental system is depicted in Fig. 1. The 1310-nm data was generated using a directly modulated Fabry–Perot laser biased near threshold. A polarization-maintaining 3-dB coupler, designed for 1550-nm-light, passed about 80% of the 1310-nm data signal toward the DFB SOA. We used a tunable laser to provide the continuous-wave (CW) probe, which interacted with the Bragg resonance located at the long-wavelength edge of the DFB stop band. Optical signals were coupled in and out of the DFB SOA via tapered fibers; coupling was assisted by an antireflection (AR) coating (optimized for 1550-nm light) applied to the input facet. An erbium-doped fiber amplifier (EDFA) boosted the converted signal, and a tunable filter reduced the amplified spontaneous emission. Converted signals were measured using a 25-GHz detector and a 20-GHz digital sampling oscilloscope. Input powers were measured at the input fiber before the DFB SOA. Converted-signal powers were scaled by the output-branch gain to give power values within the fiber, before the EDFA.

III. RESULTS AND DISCUSSION

Two types of wavelength-converted signals are shown in Fig. 2, where the DFB SOA was biased at 96% of the lasing threshold. Polarity-preserved data transfer [e.g., at 1547.707 nm in Fig. 2] occurs for most probe wavelengths tuned on

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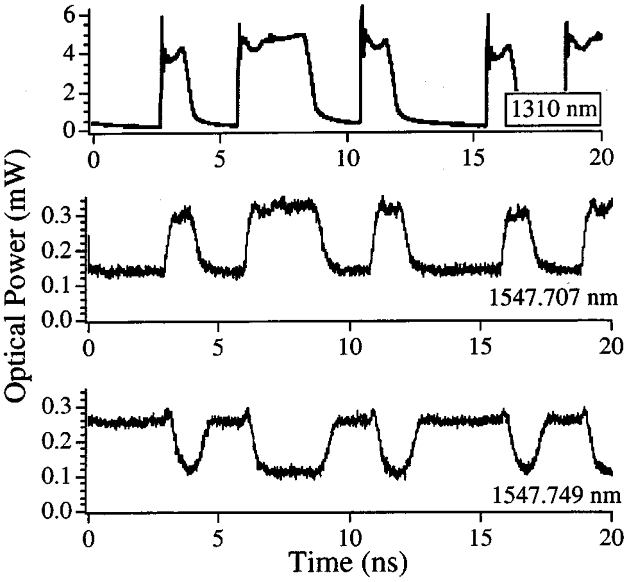

Fig. 2. Wavelength conversion from a 1310-nm, 622 Mb/s, "10 110 100" NRZ input signal. Polarity of converted signal depends on probe wavelength.

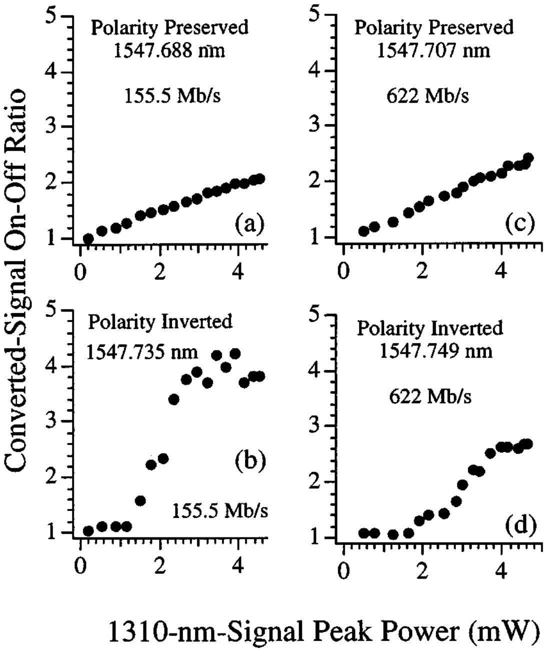

Fig. 3. Transfer function of wavelength-converted signals. Polarity-preserved signals exhibit a near-linear increase in on–off ratio, while polarity-inverted signals exhibit a digital-like transfer function.

the short-wavelength side of the Bragg resonance. The probe experiences a transient increase in its transmission because the pump-induced decrease in refractive index shifts the Bragg resonance into the probe wavelength. Transmission is also increased by the accompanying increase in gain which strengthens the Bragg resonance. We have avoided, however, pump levels that strengthen the Bragg resonance so much that a measurable signal is generated even without a probe beam [4].

Polarity-inverted conversion [e.g., at 1547.749 nm in Fig. 2] occurs for probe wavelengths tuned near or on the long-wavelength side of the Bragg resonance. In this case, the pump-induced decrease in refractive index moves the Bragg resonance *away* from the probe wavelength, decreasing the output power. This process can be assisted by the positive feedback loop that gives rise to downward bistable switching in DFB SOA's [7]; the decreased probe power within the device allows the carrier density to recover, reducing the refractive index and shifting the Bragg resonance further away from the probe wavelength.

In addition to data polarity, the two types of wavelength conversion are distinguished by their transfer function, as shown in Fig. 3. On–off ratios (for all data) are measured using an alternating "10" RZ data pattern. For polarity-preserved signals, this ratio grows almost linearly with the peak input-power. However, polarity-inverted signals exhibit a nonlinear, digital-like transfer function, unique among of wavelength-conversion demonstrations [1]–[4]. The relatively flat high- and low-contrast regions are advantageous because they can perform signal reshaping, thereby decreasing the bit-error rate. At 155.5 Mb/s, an on–off ratio of about 4 extends over an input-power dynamic range of 2 mW, for a device driven at 98% lasing threshold [see Fig. 3(b)]. We expect this range to extend much further, thus removing the need for an input-power control scheme.

Experiments were performed using a commercial, multiquantum well (MQW), DFB laser (below threshold). The change in refractive index (embodied by the linewidth enhancement factor α) was engineered to be small by using a quantum-well active region and a Bragg wavelength 16 nm shorter than the gain-peak wavelength. We expect larger on–off ratios from devices designed to provide large α (bulk gain, and relatively longer Bragg wavelength). The on–off ratio can also be improved by optimizing the grating strength, or by introducing grating nonuniformities such as a phase-shift or spatial chirp [7].

Relatively high 1310-nm-signal powers (~ 4 mW) were required to pump the SOA, but this power level can be reduced by optimizing the coupling efficiency. Many advantages occur, however, *because* the role of the input signal is to pump the SOA. We found complete extinction of the 1310-nm signal during the conversion process. Therefore, a post-conversion optical filter is not required to remove the injected data signal. Data transfer was also found to be transparent to the polarization state of the 1310-nm light. Furthermore, data transfer occurred for input signals propagating in the same or opposite direction with respect to the probe signal. We also expect that the same device can convert data from all wavelengths in the 1310-nm communication window.

Using a probe power of 3.9 μW, it was common to realize $>$15-dB fiber-to-fiber conversion gain at the signal peaks (18 dB for Fig. 2). The on–off ratio was maximized by aligning the probe polarization with the transverse-electric (TE) mode of the SOA. We measured the wavelength range of the probe to be 0.068 and 0.02 nm for polarity-preserved and polarity-inverted signals, respectively. Since these spectral ranges are small, data can only be transferred to a single WDM communication channel. However, this may not be a limitation for modern lightwave systems designed with pre-specified standard channel wavelengths. Indeed, wavelength converters for each channel can be designed using the technique proposed here.

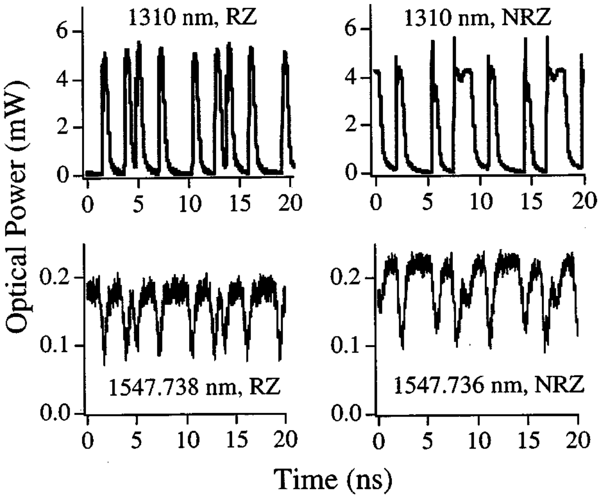

Fig. 4. Patterning effects at 900 Mb/s for RZ and NRZ signals with a "10 110 100" data sequence.

Precise alignment of the probe wavelength and DFB resonance can be achieved by integrating both devices onto the same chip, using an electron beam to write each grating. Alignment can also be performed by tuning the Bragg resonance via the injection current. Using polarity-preserved data, for example, a decrease of 0.38 mA (2% of threshold) accommodated a probe-wavelength increase of about 0.03 nm. Similar on–off ratios were maintained at the same data rate (155 Mb/s) and even at 622 Mb/s, as shown in Fig. 3(c).

As the data rate approaches the carrier lifetime ($\sim$1 ns), the on–off ratio is expected to decrease. For polarity-preserved conversion, however, the high optical intensity effectively reduces this lifetime through stimulated emission. Polarity-inverted data, with lower intensity, is compromised even at 622 Mb/s, as shown in Fig. 3(d) at 98% threshold (similar performance at 96%). At faster rates of 900 and 1250 Mb/s, the on–off ratio dropped to 2.3 and 1.7, respectively. Using a "10 110 100" data sequence, serious pattern effects were observed above 1 Gb/s resulting, in part, from the modulation bandwidth of the 1310-nm diode laser. Pattern effects began near 700 Mb/s, and became large at 900 Mb/s for NRZ data, as shown in Fig. 4 (98% lasing threshold), but remained small for RZ input and converted data. Although high-speed optical networks are moving beyond 10 Gb/s, bit rates below 1 Gb/s remain viable candidates for local-access systems.

IV. CONCLUSION

We have demonstrated a novel, all-optical, 1310-to-1550 nm wavelength-conversion technique based on direct optical pumping of an ordinary DFB laser (driven below threshold). Polarity-inverted conversion exhibits a digital-like transfer function with an on–off ratio of 4 at 155.5 Mb/s; improvements should be possible with design changes such as a phase-shifted grating. The relatively low cost, data-polarization transparency, digital-like transfer function, large (expected) dynamic range for both input–data power and wavelength, and speed of this wavelength-conversion technique make it appropriate for local-access lightwave systems. Bit-error-rate testing and on–off ratio measurements using pseudo-random binary-sequence data (both beyond the capabilities of our equipment) are required for further characterization and assessment.

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