torted, while the replica pulse at +3.9 ps is broadened and suppressed. Similar results are obtained from simulation using the actual nonlinear spectral dispersion function.

5. Conclusion

We have demonstrated the importance of the nonlinear distribution of pixels in the frequency domain for broadband pulse shaping. In particular, we have shown that this nonlinear distribution can strongly affect replica pulses arising in LCM based pulse shaping and can be used to suppress their intensity.

6. Reference

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CTuV

4:45 pm–6:30 pm
Room 318/320

Telecom Components

David A. Ackerman, *Bell Labs., Lucent Tech., USA, President*

CTuV1

(Tutorial)

4:45 pm

Semiconductor Lasers for WDM Systems

Paul A. Morton, *CIENA Corporation*

This tutorial will provide an introduction to the wide range of laser devices used in current and future commercial WDM transmission systems. The talk will start with a high level description of WDM systems (Metro and Long-Haul), and point out the various classes of lasers used for each application. This will be followed by a more in-depth description of the different devices, and their important performance parameters. The talk will try to cover all types of lasers, including:

- i) Low Cost modules for the client interfaces of WDM systems: Transceivers, Transponders, Parallel Optics (using VCSEL transmitter arrays for low cost system interconnects).
- ii) Sources for WDM transport, including directly modulated DFB's Integrated DFB/EA modulators, CW lasers + Lithium Niobate modulators, Tunable lasers—for use at 2.5G, 10G, 40G, then in the future 100G/160G?
- iii) Pump lasers for EDFA's and Raman Amplification, from low cost/low power to high performance devices.

The final section of the talk will look towards the future, describing new devices to be used in the coming years and major trends seen for components and integrated modules.

Biography

Paul Morton was born in Stockton-on-Tees in the North-East of England. He received his B.Sc., M.Eng. and Ph.D. in E.E. from the University of Bath. He moved to the USA in 1988 as a postdoctoral researcher at U.C. Santa Barbara, then to AT&T Bell laboratories, Murray Hill, where he carried out research on high performance lasers. He interned at the Optoelectronics Business Unit (then Lucent) to learn the business of making and selling lasers. Paul moved to CIENA in 1997, where he is Director of Active Photonic Components, leading a team which carries out R&D on lasers and qualifies them for use in CIENA systems. He also leads the CIENA 40G technology project.

CTuV2

5:45 pm

Extremely Broadband Tunable Semiconductor Lasers for Optical Communication

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1. Introduction

Broadband characteristics are important for optical communication. Thus, many efforts are devoted to expanding bandwidth. Recent technology has made optical fibers exhibit extremely broad bandwidth, covering nearly from 1200 nm to 1600 nm with the loss less than 0.5dB/km.¹ However, The abundant bandwidth of fibers is still far from being fully exploited even with the bandwidth of Er-doped fiber amplifiers and lasers expanded from C-band (1525 nm to 1565 nm) to L-Band (1570 nm to 1610 nm). Semiconductor lasers/amplifiers using multiple-quantum-well (MQW) engineering,^{2–4} thus provide alternatives other than Er-doped fiber for the broadband purpose. This work reports the study on the design of MQWs for broadband semiconductor lasers/amplifiers. The study shows that, with properly designed sequence of nonidentical MQWs made of InGaAsP/InP materials, the emission bandwidth could be nearly 300 nm. Using the designed MQWs as the laser gain material, the external-cavity semiconductor laser exhibits an extremely broadband tuning range, covering from 1300 nm to 1540 nm.

2. Experiment—Device Fabrication and Emission Spectrum

The designed quantum-well structure for broadband purpose has two In_{0.53}Ga_{0.47}As QWs near the n-cladding layer and three In_{0.67}Ga_{0.33}As_{0.72}P_{0.28} QWs near the p-cladding layer. The quantum wells are separated by wide In_{0.86}Ga_{0.14}As_{0.3}P_{0.7} barriers. The quantum-well structure was grown using MOCVD. Bent-stripe ridge-waveguide semiconductor-laser amplifiers (SLA's) were fabricated on those substrates.⁵ The device length is about 500 μm. Typical processing techniques were used for the device fabrication. The ridge waveguide was created by RIE. No facet coatings were applied to the devices.

Fig. 1 shows the measured emission spectra of the fabricated SLA's at different injection currents. The emission at the low injection current occurs at the wavelength corresponding to the n = 1 transition in the In_{0.53}Ga_{0.47}As QWs. The emission contribution from the In_{0.67}Ga_{0.33}As_{0.72}P_{0.28} QW is not obvious until the injection current increased to above 300mA. The measurement shows that the emission bandwidth could be nearly 300 nm, covering from less than 1300 nm to over 1550 nm. Even broader bandwidth is still possible by increasing the injection current or fine tune of the QW width.

3. Experiment—Tuning Range

The above SLA is used in the external cavity for tuning experiment. Fig. 2 shows the setup of the external-cavity semiconductor laser. The grating is Al coated with 600 lines/mm. With the broad gain bandwidth, the semiconductor laser has an extremely broadband tuning range. It covers from 1300 nm to 1540 nm, which could serve as the complementary to the Er-doped fiber laser to explore the broad bandwidth of fibers for optical communication. For low-injection current, the tuning range mainly lies around 1500 nm. Increasing the injection current, the tuning range gradually extends to the 1300 nm band. The tuning behavior corresponds to the emission spectra shown in Fig. 1 pretty well. Fig. 3 shows the tuning spectra at different wavelengths. The broadband tuning range also indicates that almost the entire emission spectrum shown in Fig. 1 could serve as the gain for laser oscillation and so should also be useful for amplification purpose. Even broader tuning range is expected with fine adjustment of lasing conditions or better designed MQW structures.

CTuV2 Fig. 1. The measured spectra of the SLA at different injection-current levels.

CTuV2 Fig. 2. The setup of tuning experiment using external-cavity configuration.

CTuV2 Fig. 3. Tuning spectra at different wavelengths (linear scale).

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CTuV3 6:00 pm

Wideband integrated multiple laser chip on 1.55 μm heterostructure using controlled bandgap tuning by quantum well intermixing

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The ongoing growth of telecommunication network capacity requires complex optical systems for DWDM applications. With new systems being developed for C and L band, the number of new high performance devices is increasing significantly. Post growth processing techniques for wide bandgap tuning of 1.55 μm wafers are an attractive approach for the fabrication of higher performance, monolithically integrated lasers and modulators. Quantum well intermixing (QWI) is a key technology for the fabrication of advanced photonic integrated components

(PICs) requiring integration of multiple bandgap values over a 150 nm range on a single substrate.^{1,2} The QWI technique used for this work relies on the use of a low energy ion implanter, which is an apparatus commonly available in the industry. Shallow ion implantation is carried out to generate point defects near the surface of the material, i.e. well away from the active region. Following ion implantation, rapid thermal annealing is carried out to reduce implantation damage and to promote intermixing of quantum wells and barriers through point defect diffusion underneath the implanted regions. After interdiffusion, the bandgap profile of the material is increased so that the effective emission wavelength of processed devices is blueshifted by an amount directly related to the implantation dose. Standard MOCVD-grown, 1.55 μm heterostructures with five quantum wells were used for this work.

Using arsenic ion implantation, at a dose of 1.5×10^{12} ions/cm² with an energy of 360 keV, we have fabricated laser diodes whose characteristics are almost identical to as-grown devices (see fig. 1), except for a 26 nm blueshift in the emission wavelength (see fig. 2). We have also carefully checked that the annealing step alone did not have any effect on the unimplanted material, which is a key requirement for monolithic integration of multiple bandgap devices. To obtain a spatial selectivity over the blueshifting induced in our procedure, we used a variable thickness SiO₂ implantation mask that was photolithographically defined in a single step on the substrate. Depending on the specific region of the substrate,

CTuV3 Fig. 1. Light versus current intensity curves from 1.5×10^{12} ions/cm² implanted oxide stripe laser devices (a), annealed only (b) and reference devices (c).

CTuV3 Fig. 2. Normalised lasing spectra from 1.5×10^{12} ions/cm² implanted oxide stripe laser devices (a), annealed only (b) and reference devices (c).

CTuV3 Fig. 3. Normalised lasing spectra from the ten channel monolithic laser devices.

the thickness of the implantation mask took one out of ten values covering the range from complete transparency up to full stopping of ions. Phosphorus ion implantation, at a dose of 1×10^{14} ions/cm² with an energy of 360 keV, was then carried out followed by a rapid thermal annealing step. The electroluminescence spectra from the ten channel monolithic devices are shown in fig. 3. The integrated devices emission wavelength range extends over 80 nm, which covers the equivalent of the ITU³ grid wavelengths (C band). The variation in the threshold current density among the devices was found to be limited to only about 17% (going from 1.2 kA/cm² to 1.4 kA/cm²).

In conclusion we have shown that low energy ion implantation induced QWI is an attractive method for post growth single step multiple bandgap tuning of high quality active and passive devices as well as PICs.

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CTuV4 6:15 pm

Monolithic fabrication of 2 x 2 crosspoint switches in InGaAs/InAlGaAs multiple quantum wells using quantum well intermixing

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Optical switching and packet routing are highly desirable functions in optical communication networks. The requirements of both a high switching speed and low insertion loss can be met using semiconductor devices. Here we report the monolithic integration of semiconductor optical amplifiers (SOAs), electro-absorption (EA) modulators, and passive power splitters and combiners to form 2 x 2 crosspoint switches.

Because of the need to integrate gain, modu-