Leading Edge Photonic Technologies

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ABSTRACT

The impact of photonic device research on future lightwave systems, in particular, those that use wavelength-division multiplexing (WDM), is discussed. WDM techniques that maximize the capacity of fiber require increasingly complex transmitters and receivers. Examples of current state-of-the-art prototype devices are presented in which this complexity is built into monolithic photonic integrated circuits.

1. Introduction

Recent enthusiasm for lightwave systems within the cable television industry has been driven by rapid advances in laser technology, most notably that of linear high-power distributed feedback (DFB) lasers. Development of linearized external modulators, for use with high-power diode-laser pumped YAG lasers, and improvements in erbium-doped fiber amplifiers (EDFAs) have opened exciting new possibilities. Continued deployment of these technologies over the next few years will provide fiber-based cable networks with unsurpassed capacity and diversity of services.

Prior to this interest in analog systems, the availability of high speed lasers and photodetectors created a similar revolution in digital long-haul, loop feeder, and data networking systems. EDFAs are now enabling non-regenerated trans-oceanic lightwave systems at 5-10 Gbps over 10000 km.[1,2] New photonic device capabilities continue to drive new system concepts.

What new types of devices can be expected and how will these effect system concepts of the future? In attempting to answer these questions it is useful to consider what types of systems might be required.

Already we are seeing the merging of analog and digital services within industries that were once strictly analog or digital. Of course, we always see potential applications for increased capacity. Hence it is essential that future systems have increased capacity, and flexibility in the way in which services can be provided. Wavelength-division multiplexing (WDM) is key to increasing both capacity and flexibility. Yet the photonic devices required for all but the simplest forms of WDM remain confined to research laboratories.

As long as the access to the subsciber is either coaxial cable or twisted pair, then the system capacity must always be constained by this bottleneck in the distribution plant. One must imagine that fiber will, some day, be viable all the way to the home. This will required drastic reductions in the cost of photonic transmitters, receivers and multiplexors. Photonic integration, in which sources, detectors, interconnecting waveguides, electronic devices and passive optical components are fabricated as integrated circuits in one material system, are key to reaching cost targets.

This paper discusses recent milestones resulting from photonic device research, as applicable to these future possibilities.

2. Wavelength Division Multiplexing

Three categories of WDM can be defined. The first and simplest uses fiber WDM couplers to combine and separate sources at 1.3 and 1.55 μm wavelengths. This will be referred to as μm-WDM, and is feasible with technology that is readily available. It provides a convenient way to reduce fiber requirements by a factor of two, increase channel capacities, or diversify services.[3]

Next, far greater capacities can be realized if multiple wavelengths are used within each of the 1.3/1.55 μm wavelength windows. Since each of these windows are in the order of 50 nm wide, dramatic increases are possible with channel separations as narrow as 1 nm. (1 nm = 10 Å = 130 GHz = 0.001 μm)

These nm-WDM techniques require multiplexor properties that cannot generally be obtained from fiber WDM couplers. Integrated planar waveguide WDMs are required to achieve suitable channel densities.[4] Fiber Fabry-Perot filters can be used to select channels. Optical sources must be manufactured to exact specified wavelengths, or must be broadly tunable over the entire wavelength window. The operating wavelength must then be locked to within approximately 1 Å from the center wavelength of the channel. Frequency-locking lasers to within this large margin for error is reasonably straightforward. If these technical issues are overcome, nm-WDM techniques have great potential.

The third, and ultimate WDM technique involves optical channel frequency separations that are in the order of a few GHz, hence this will be referred to as GHz-WDM. Various coherent and direct-detection techniques have been researched that enable this highly efficient use of optical bandwidth.

Direct detection can be used for GHz-WDM in two main ways. The simplest approach is to modulate the intensity of each carrier with an external modulator, then select each modulated channel with a narrow optical filter. An alternative approach is to modulate the frequency of the optical carrier. New tunable laser structures are ideal for this. An optical filter can then be used as an optical frequency discriminator to pass only the desired channel, and simultaneously convert the FM to intensity modulation (IM). One then simply detects the IM on a photodetector.

For a considerable increase in complexity, coherent detection can provide slightly higher spectral efficiency. Carrier (optical) frequencies must be controlled to within fractions of 1 GHz. The polarization of the received signal must be controlled, or polarization diversity techniques must be used. Laser linewidths must be small. Considering the complexity, it is difficult to imagine a system application that will require the capacity for which coherent transmission is essential. Yet, since coherent represents the ultimate in capability, research continues.

Given the potential of nm-WDM, why might GHz-WDM ever be needed? With 10 GHz channel separations, each wavelength window could support 500 channels, each with a bandwidth of a few GHz. Therefore it is unlikely that ultimate bandwidth will be the issue. The choice will eventually be made based on how photonic devices evolve to suit each option.

3. New Photonic Devices

The ideal source for nm- or GHz-WDM systems would be tunable over an entire wavelength window (50 nm). This could then be used with an external frequency-lock circuit as a source for any desired channel. Several tunable lasers have been invented. The tunable distributed Bragg reflector (DBR) laser [5] has great potential, but the best tuning range reported to date is less than 10 nm. A new approach [6] has resulted in the demonstration of a tuning range greater than 50 nm.

Broad tunability is achieved with this new structure, shown in Figure 1. The laser consists of a gain section, pumped by current I_g, and a tunable filter. Current I_t controls the wavelength allowed to circulate throughout the vertical coupler filter (VCF) structure. The VCF is the key to broad tunability.

The grating on the upper edge of the upper active waveguide allows power to couple to the lower passive waveguide. Varying I_t varies the wavelength that is coupled. Light of the appropriate wavelength couples to the lower waveguide, is reflected from the cleaved reflector, and then returns to the upper waveguide. The VCF structure provides an enhancement in the tuning range of the filter, for a given amount of tuning current.

The tuning characteristics for the VCF laser are shown in Figure 2. Tuning of 57 nm has been demonstrated. The tuning current was pulsed at for extreme values to minimize heating within the chip. Work continues on understanding and optimizing the performance of these devices.

One reason to favor GHz-WDM over nm-WDM has been the limited tuning range of the lasers. With a limited tuning range it is advantageous to maximize the bandwidth accessible to each laser. The high spectral efficiency offered by GHz-WDM then appears worth the added complexity. Devices with extremely broad tunability remove this limitation, adding strength to nm-WDM opportunities.

In addition to broadly tunable sources, simple means to modulate the optical carrier must be developed. Direct laser modulation is adequate for intensity modulation (IM) if chirp (unintentional frequency modulation (FM)) is tolerable. If FM modulation of the optical carrier is desired then new laser structures can provide reasonably pure FM. But nm- or GHz-WDM applications may require pure IM, or phase modulation (PM). This requires external modulation. Unfortunately, coupling a tunable laser made from InP-based semiconductor material to a polarization-dependent external modulator made from $LiNbO_3$ will likely remain expensive.

The solution lies in fully integrated laser-modulators, all made in the InP material system. Figure 3 shows a prototype device that couples a tunable DBR laser to an elecro-absorption modulator[7]. Unlike the more common interferometric intensity modulators, this modulator operates by varying the absorption of the material in the layer that has a bandgap energy corresponding to 1.1 μm wavelength. The multiple quantum well (MQW) stack provides gain for the DBR laser formed between the grating and the outside edge of the MQW stack. Light from this laser overlaps the absorbing 1.1 μm layer and is modulated before exiting the anti-reflection coated facet. The DBR laser is tunable over several nm wavelength.

Devices such as those presented so far will open the way for nm-WDM and some forms of GHz-WDM. Coherent systems would require such devices, but if costs are to ever be reasonable, several types of devices must be integrated into low cost modules. Photonic integration has the potential to combine these devices on low cost mass-producible semiconductor chips.

An example of an integrated photonic circuit for a coherent receiver[8] is shown in Figure 4. Here the local-oscillator (LO) laser, combining coupler, waveguide interconnects and balanced receiver are combined onto one chip.

The LO laser is a 3-section broadly-tunable (10 nm) DBR laser. Signals received in the input waveguide are combined with the LO in the directional coupler. Both outputs of the coupler are detected by a pair of photodetectors.

This photonic integrated circuit has been tested for coherent digital transmission at several hundred Mbps. It does not provide polarization control or polarization diversity, an additional complication that must be addressed.

N. Conclusions

Several new photonic devices have been presented. By increasing the complexity of the device structures, effectively combining several devices into one monolithically fabricated photonic circuit, these devices have the potential to make futuristic WDM proposals into reality.

Unfortunately, years of development are required before these research prototypes become components for widespread deployment. The cost of such development cannot be justified without the definition of applications that require the enormous capacities offered. Such requirements may not appear until far in the future, when fiber extends all the way to the subscriber. Meanwhile, new photonic devices will continue to emerge, inspired by the demands of increasingly imaginative system applications.

The devices presented were conceived and produced by T. L. Koch, U. Koren, B. I. Miller, M. G. Young, R. C. Alferness, C. A. Burrus and a large group of collaborators at AT&T Bell Laboratories.

REFERENCES

1. N.S. Bergano,"Optical amplifier undersea lightwave transmission systems," Paper No. WF4, *Tech.Digest*, OFC '92, San Jose, CA, p. 117, Feb. 1992.

2. L. F. Mollenauer, E. Lichtman, G. T. Harvey, M. J. Neubelt, B. M. Nyman, "Demonstration of error-free soliton transmission over more than 15,000 km at 5 Gbit/s, single-channel, and over 11,000 km at 10 Gbit/s in a two channel WDM," Paper No. PD10, *Post Deadline Proceedings*, OFC'92, San Jose, CA, pp. 351-354, Feb. 1992.

3. M. R. Phillips, A. H. Gnauck, T. E. Darcie, N. J. Frigo, G. E. Bodeep, E. A. Pitman, "112 Channel WDM split-band CATV system," Paper No. PD6, *Post Deadline Proceedings*, OFC'92, San Jose, pp. 336-339, Feb. 1992.

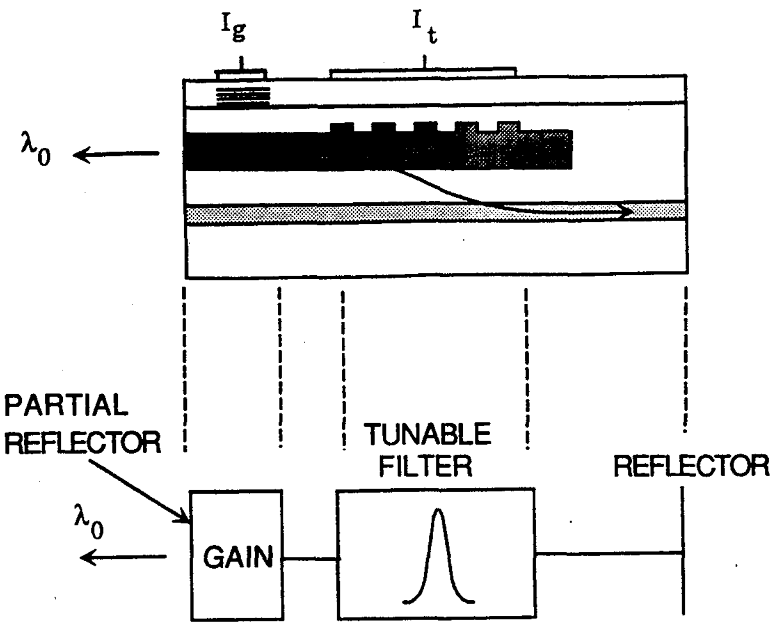
4. C. Dragone, "An NXN Optical Multiplexer Using a Planar Arrangement of Two Star Couplers," *IEEE Photonics Technol. Lett.*, vol. 3, no. 9, pp. 812-815, Sept. 1991.

5. T. E. Darcie, "Emerging photonic technologies for lightwave CATV systems," SCTE Fiber Optics Plus '92, San Diego, CA, Jan. 1992.

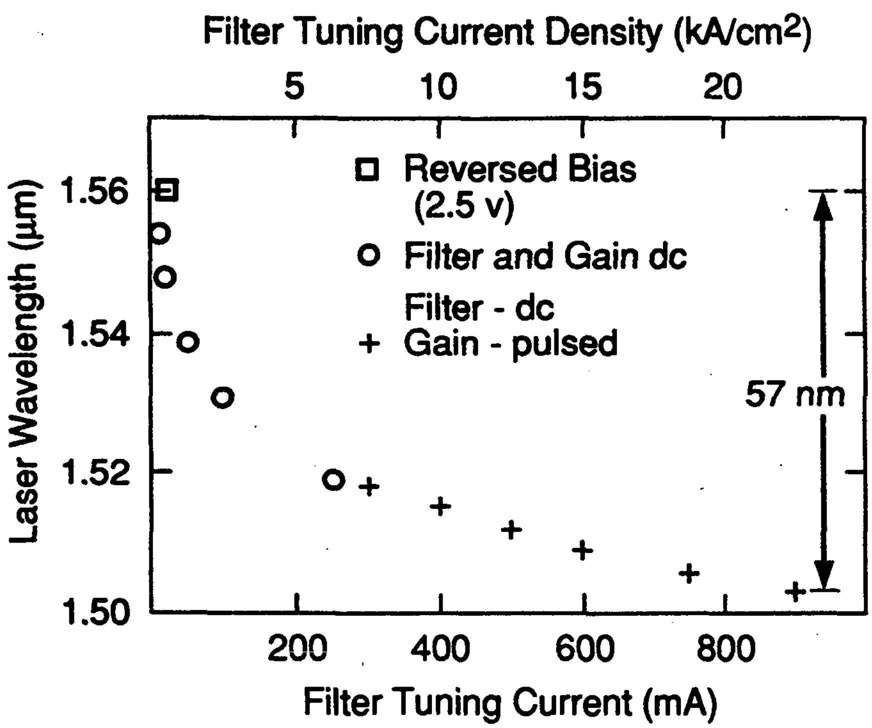
6. R. C. Alferness, U. Koren, L. L. Buhl, B. Miller, M. G. Young, T. L. Koch, G. Raybon, C. A. Burrus, "Widely tunable InGaAsP/InP laser based on a vertical coupler intracavity filter," Paper No. PD2, *Post Deadline Proceedings*, OFC'92, San Jose, pp. 321-324, Feb. 1992.

7. P. D. Magill, K. C. Reichmann, R. Jopson, R. Derosier, U. Koren, B. I. Miller, M. Young, B. Tell, "1.3 Tbit km/s transmission through non-dispersion shifted fiber by direct modulation of a monolithic modulator/laser," Paper No. PD9,*Post Deadline Proceedings*, OFC'92, San Jose, pp. 347-350, Feb. 1992.

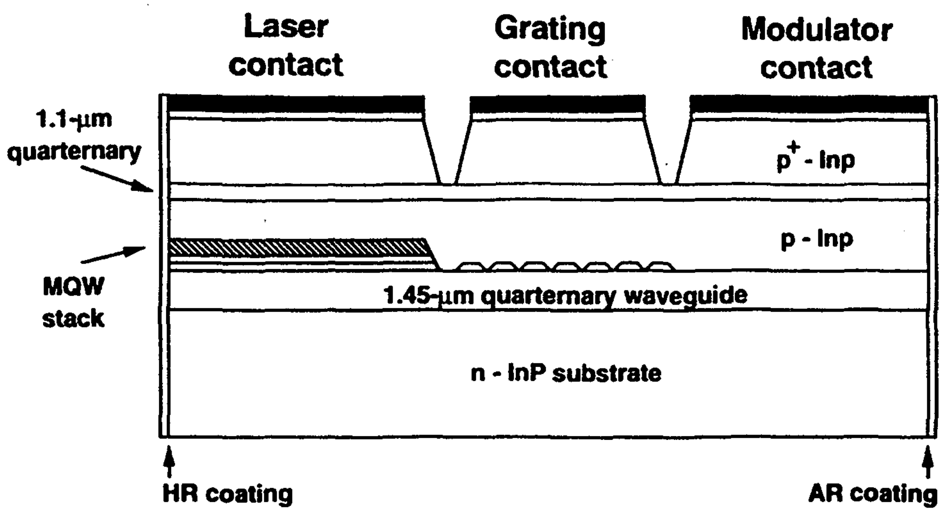
8. T.L. Koch, F.S. Choa, U. Koren, R.P. Gnall, F. Hernandez-Gil, C.A. Burrus, M. G. Young, M. Oron, and B. I. Miller, "Balanced Operation of an InGaAs/InGaAsP Multiple-Quantum-Well Integrated Heterodyne Receiver," *IEEE Phot. Tech. Lett.*, vol. 2, pp. 577-580, 1990.



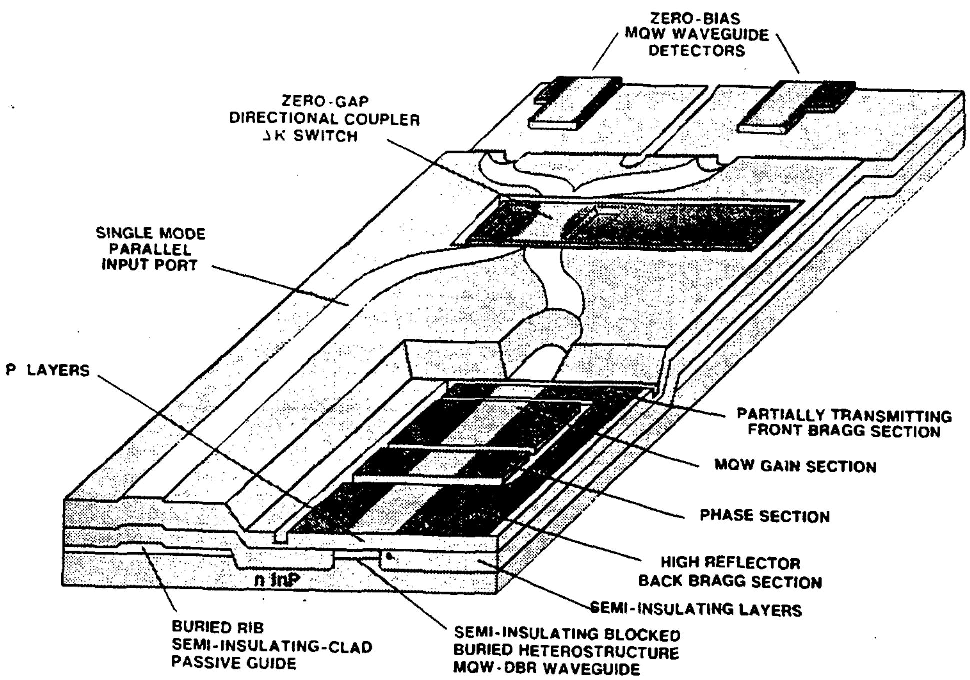
1. Widely tunable vertical coupler-filtered laser. Optical cavity is uses both upper and lower waveguides as indicated by the arrows.



2. Tuning capability of vertical coupler-filtered laser.



3. Integrated tunable DBR laser and electro-absorption modulator.



4. Photonic integrated circuit that combines the components required for a coherent receiver. The local-oscillator laser, which is a tunable DBR laser, a waveguide power combiner and photodetectors are included on the same substrate.