Spectrometer on a chip: InP-based integrated grating spectrograph for wavelength-multiplexed optical processing

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ABSTRACT

We report the performance of an InP-based integrated spectrometer and consider its application in wavelength division multiplexed (WDM) systems. The wavelength multiplexer / demultiplexer operates in the 1.5μm fiber band and disperses 1nm spaced signals over a spectral range of 75nm. Cross talk between the channels is -19dB and the optical performance of the spectrometer is essentially insensitive to the polarization of the incident light. Use of the device in multi-wavelength telecommunication and computer local area networks is discussed.

1. INTRODUCTION

Wavelength division multiplexed (WDM) systems are currently attracting a considerable degree of interest for optical communications, both in the area of telecommunications [1] and computer local area networks [2]. There is also emerging interest in the use of multi-wavelength optical links for board-to-board and chip-to-chip interconnects in complex high speed multi-processor environments.

Communication by optics offers, of course, the advantages of a very high bandwidth, freedom from electromagnetic interference, and the potential for providing communication at a lower power consumption than is possible with comparable electrical connects. Using multi-wavelength communication increases many fold the available bandwidth and in addition provides a convenient way of communicating independent signals without cross-talk on the same line, confering signal 'transparency' and, at the chip-to-chip and board-to-board level, also relieving the increasingly vexing problem of providing the chip or board with the large number of independently routed electrical connections it requires.

In the telecommunication arena, several WDM and FDM systems have been proposed and are currently under examination. In our discussion, here, we are concerned only with WDM systems where we have amplitude modulated signals and direct detection receivers. In such systems the wavelength separation between channels is in the region of a nm or so.

Although wavelength multiplexing may be used simply to increase the capacity of a point-to-point communication, for example in a long distance inter-exchange link, most interest in WDM systems lies in the use of the wavelength diversity as an defining role in the signal network. Most intensively studied have been broadcast-and-select and wavelength routing networks. In the former, either the transmitters, the receivers, or both, are wavelength-selective or wavelength-tuneable.

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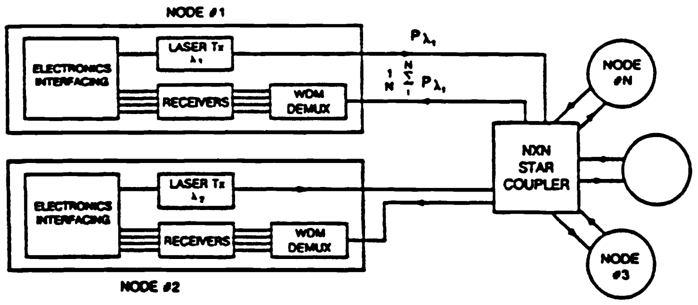

Figure 1. LAMBANET: an example of a broadcast and select WDM architecture

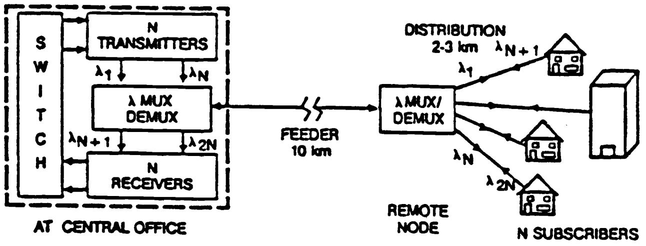

Figure 2. The passive photonic loop. Using WDM routing to provide user services, while retaining the opto-electronics and powering in the central office.

Bellcore's TMLAMBANET demonstration [3] is an example of a broadcast and select network, where the transmission wavelength of each source is fixed and the receivers are wavelength-selectable. It is illustrated in Figure 1. Each node has a laser which transmits at a unique wavelength, in effect its source 'identifier', and the same node selects from the broadcast signals whichever wavelength-coded signal it wishes by taking the output from the receiver detecting the selected wavelength demultiplexed signal. The LAMBANET demonstration used a dielectric-based grating spectromater to disperse the different wavelength signals.

Wavelength routing, in particular optical routing using passive multiplexers and demultiplexers have been considered for telephone local loop applications. Such a scheme removes the powered and potentially vunerable optoelectronics from the end-user (as in the LAMBANET architecture) into the controlled environment of the central office. Bellcore's Passive Photonic Loop [4] is one such scheme and is illustrated in Figure 2.

In the computer arena, also, there has been considerable interest in wavelength multiplexed communication between processor units. IBM's circuit-switched multiaccess metropolitan area project, Rainbow [2], is an example.

All WDM networks require passive multiplexer / demultiplexers. To date the system demonstrations have employed small grating spectrometers, bulk or fiber Fabry-Perot interferometers or acousto-optic filters. If one could engineer a high performance monolithic semiconductor multiplexer / demultiplexer, one would gain the advantage of having a compact single unit device, with all that that implies for ruggedness, reproducibility, and unit-cost reduction. In the case of wavelength-selective or wavelength tuneable receivers, the demultiplexed optical signal is fed directly into a detector and, in this case, with a semiconductor based wavelength demultiplexing there is the immediate possibility of integrating the detection and amplification functions onto the same chip to form a single monolithic WDM receiver, thereby eliminating the stringent alignment and packaging requirements of the descrete components. Greater field-worthiness, higher performance and lower cost should result. Integration of the multiplexer with laser elements and laser driving electronics for wavelength selective or wavelength tuneable transmission are also possible. It was with these combined driving forces that we researched the technology for the InP-based 'spectrometer' described in this paper.

2. THE INTEGRATED SPECTROMETER

2.1 Performance Criteria

For a WDM system, with a wavelength spacing of the order of 1nm and a high passband/ stopband efficiency, one can envisage a system using receivers operating at several Gb/s with a total throughput capacity of several hundred Gb/s.

A 1nm / 10Gb/s combination of wavelength spacing and receiver bandwidth would make very efficient use of the available fiber band while at the same time probably allowing sufficient tolerance to accomodate fabrication variations in the muiltiplexer / demultiplexer and the laser allowing sufficient latitude for wavelength drift due to temperature fluctuations. A 1nm / 10Gb/s system requires a technology push both in order to realise the high bitrate receiver and the wavelength multiplexing/ demultiplexing components, but would confer an enormous available bandwidth of in excess of 1THz in the 1.5μm fiber band. More relaxed criteria for a 2-4nm channel spacing and 2.5Gb/s reception would still give a total system bandwidth of several hundred Gb/s.

In order to examine the potential for realising a high performing semiconductor based multiplexer / demultiplexer for use in a high density WDM system, we designed a device that would multiplex / demultiplex signals with wavelengths spaced at 1nm.

2.2 Spectrometer Design

A grating based planar waveguide design was chosen. A single vertical grating was employed in what is basically a two-dimensional version of a classic three dimensional bulk optic single grating spectrometer. Etched waveguide ridges provided single moded input and output to and from the 'optical body' of the spectrometer, and the grating was formed by etching vertically into the semiconductor waveguide material in order to generate a reflecting diffraction surface. This grating does not, of course, rotate. Rather, the wavelength demultiplexed outputs are taken from different points on the focal line segment, as in a spectrograph, and are lead off to the output 'port' by the waveguides. A diagram of the device is given in Figure 3.

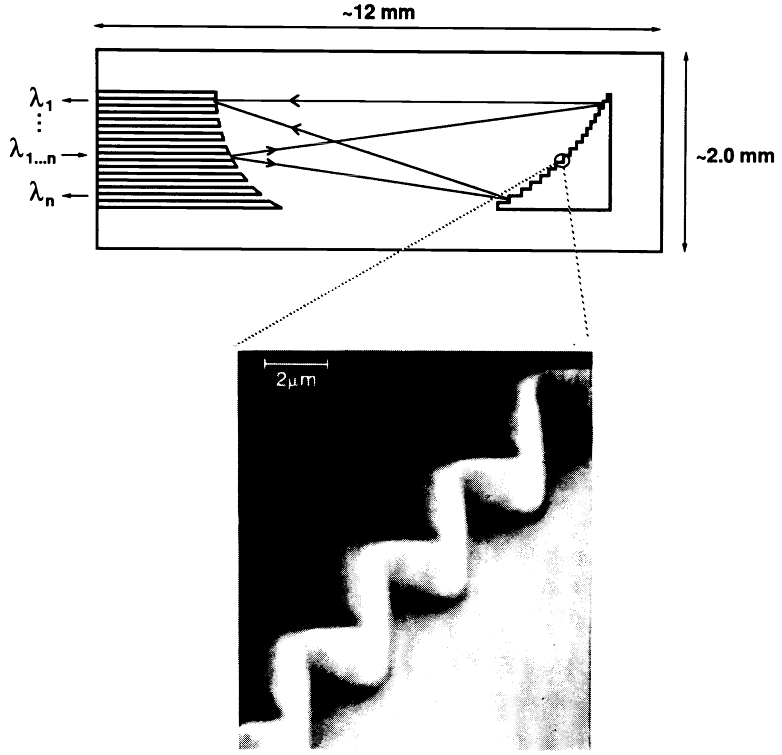

Figure 3. The integrated InP-based grating spectrometer.

The input wavelength multiplexed signal is introduced into the device via the center waveguide on the left hand side of the figure. This light then propagates along the single moded waveguide until it opens on the optical cavity. It then spreads and propagates toward the grating, whence it is reflected, diffracted, and focussed onto the focal line which falls along the locus of the waveguide ends above and below the one used as the input guide. The geometry is tailored so that the guide spacing corresponds to 1nm wavelength dispersion along this focal line. In the device presented here, the input and output guides are identical; however, the input and output guide could be differentiated in order to optimise the output 'collection efficiency' and the channel isolation and resolution.

The grating and optical cavity design follows a Rowland circle [5] construction implemented in a retro-diffracting, or Eagle, geometry. The grating was of the 'echelle' type, operating in 18th order and the grating was designed and blazed for retro-reflective diffraction at 1.51μm [6].

2.3 Device Structure and Fabrication

The waveguide material was grown by low pressure (76Torr) organo-metallic chemical vapor deposition (OMCVD). The waveguide structure used was a double heterostructure guide, InP (0.5μm) /InGaAsP(λ_g=1.0μm) (1.1μm) /InP. This weakly guiding structure was used in order to minimise the polarization dependence of the optical performance. The input / output guides were straight, equally spaced, ridge guides which opened out onto the optical cavity of the spectrometer along a segment of the focal line and terminated on the cleaved facet of the chip. The OMCVD material had less than 1% thickness variation and <2nm guide-core bandgap variation across the body of the device, allowing the spectrometer to operate with a high spectral quality.

A single photolithographic step was used to define both the focussing grating and the input / output waveguides. Chemically assisted ion beam etching (CAIBE) [7] was used to etch both structures through a photoresist mask. First, a 0.2μm etch defined the single mode guides. These were then masked from the ion beam and the grating wall etch was completed to a depth of 2.3μm. The resulting wall was vertical to <4° . See Figure 3. Finally, the chip was cleaved to give an input/output coupling facet and a single dielectric coating applied to this in order to reduce the input reflectivity (0.73% measured). The chip size was 12mm by 2mm, with ridge waveguide lengths of 0-2mm.

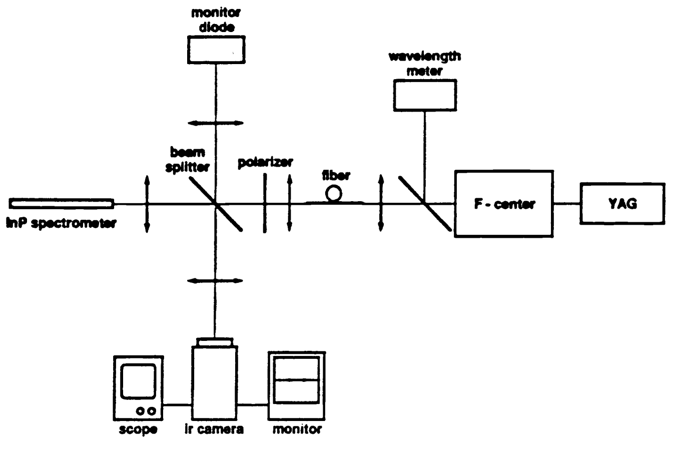

Figure 4. (above) Experimental arrangement for characterizing the spectrometer.

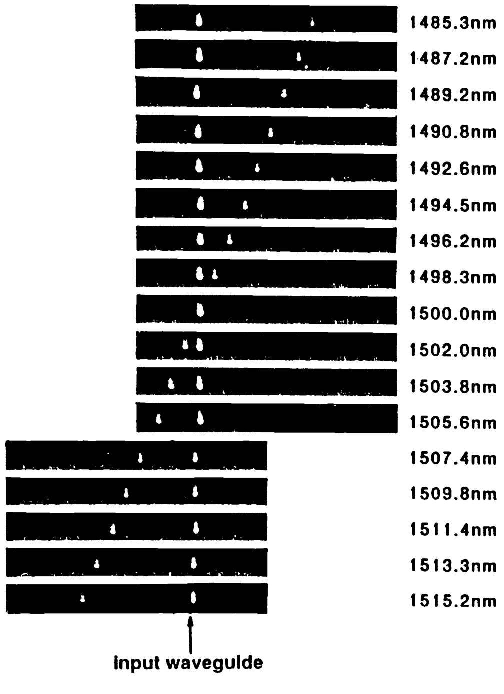

Figure 5. (right) Wavelength dispersed emission from the output guide facet.

2.4 Optical Performance

The performance of the multiplexer / demultiplexer was evaluated using an F-center laser with a 1.5GHz effective bandwidth, tunable over the range from 1.47μm to 1.57μm. Light was coupled into the device with a microscope objective, and this lens was also used to collected the light emerging from the output guides; the near-field image of input/output facet was focussed onto a calibrated i.r.vidicon. The experimental arrangement is shown in Figure 4. The evaluation was made for the device acting as a demultiplexer, changing the wavelength of the light coupled into the central waveguide and examining the output from the other waveguide end-facets.

a) Spectral Range

Wavelength demultiplexed output was observed from the 78 output waveguides etched into the material, at a wavelength spacing of 1nm. The output wavelength are plotted against channel (i.e. waveguide) number in Figure 5. Wavelength dispersed output is obtained from 1.4788μm to 1.5530μm, in accord with the calculated dispersion. A montage of the emission from every second guide around the central input guide is shown in Figure 6, labelled by the wavelength of the emission.

Although basically linear, some slight non-linearity is observed in the dispersion shown in Figure 6. This is almost entirely geometric in origin, arising from the equal guide spacings and may be corrected by adjusting the guide spacings appropriately. The relative emission power of the demultiplexed signals is shown in Figure 7. This records an effective spectral pass-band of 35nm. The reduction in the coupling efficiency away from the central, retro-reflecting, guide is caused primarily by the non-optimal blaze as one goes further away from the center; this may be largely compensated for by employing a tripartite grating, as is the practice in some commercial bulk grating spectrometers. The thin curved line 'drawn in Figure 7 shows the 'limiting efficiency', determined by the Fraunhoffer diffraction envelope for the grating.

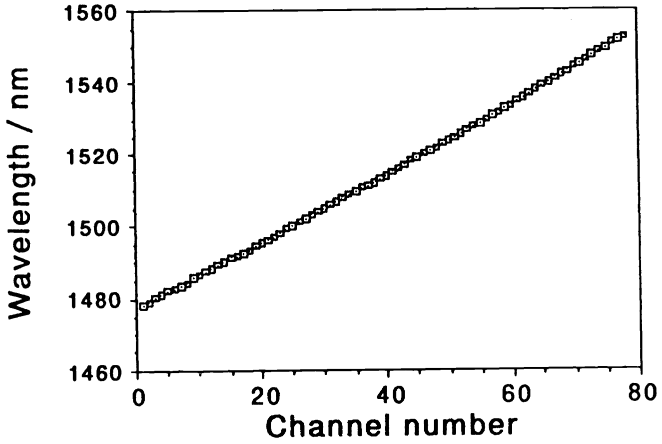

Figure 6. Emission wavelength against channel (waveguide) number; the input is the central waveguide.

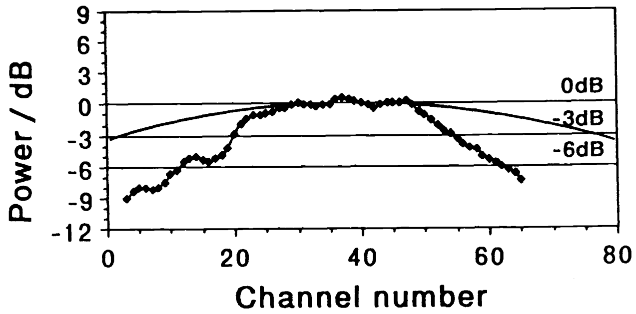

Figure 7. Relative coupling effeciency into the wavelength dispersed channels.

By scanning the wavelength across one output wavelength, the optical output pass-band of an individual channels was evaluated to be 3-3.5Å (FWHM). This pass-band corresponds to the calculated diffraction-limited value, and its attainment is testament to the high uniformity of the OMCVD grown material and to the high quality definition of the CAIBE etched grating.

b) Polarization Sensitivity

Polarization independence is extreemly important for ease of operation of a multiplexing device, removing as it does the necessity of separating, rotating, and then recombining one polarization in order to present a unique polarization to a polarization-sensitive device. Because of the low birefringence of the waveguide structure used here, the performance of the device for TE incident light is closely similar to the response for TM polarized light. The peak throughput wavelengths for TE excitation occurs at just 0.22nm higher wavelengths than for TM polarized light. Significantly, this wavelength difference is less than the optical pass-band of the demultiplexed channel, at 0.3-0.35nm, indicating that polarization-insensitive operation is possible. This was verified experimentally by tuning the input wavelength mid-way between the TE and TM peak wavelengths, for which no polarization dependence was observed.

c) Cross-talk

An idea of the cross-talk for the demultiplexer is given by Figure 8. Figure 8(a) is the vidicon trace of the light emerging from the input/output cleaved facet when a single wavelength is incident. The 'background' light emerging from guides far distant from the'output guide' is typically -30-35dB with respect to the input signal. The intensity of light emerging from the waveguides close to the 'output guide' is somewhat greater, as may be discerned in Figure 8(a). This cross-talk tends to be random in nature and most probably arises from imperfections in the output guide ridge which cause inter-guide coupling. In Figure 8(b), we show an overlay of the traces from the 8 channel wavelengths around that shown in Figure 8(a). The cross-talk experienced by the middle channel output, from the other channels all combined, is evaluated to be -19dB±2dB, which was found to be typical of the cross-talk for the other outputs across the spectral range. This value, which was not perceptibly polarization dependent, is low enough for many system applications.

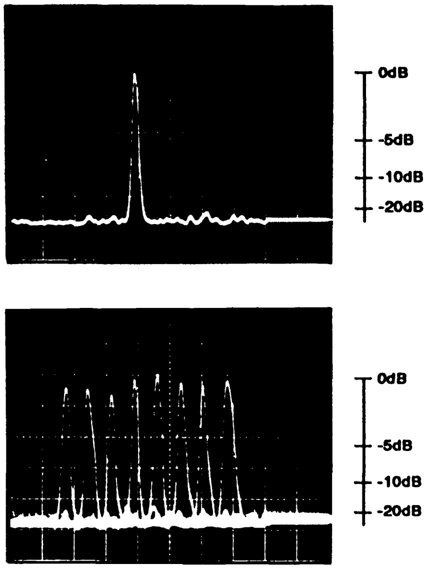

Figure 8. Vidicon trace of the output facet emission:
(a) for a single wavelength input, and
(b) superimposed emission for 8 channels.

d) Insersion loss

The insersion loss of this device was rather high, with an on-chip loss of around 16dB. However, 5.6dB of this was due to the fact that the vertical grating was not reflection coated; most light simply passed through the grating into the air beyond. Of the remaining 9-10dB, 1-2dB may be attributed to waveguide loss. The remainder is diffraction grating loss, which is in part due to the reflection of light down into the substrate (the grating wall is not quite vertical) and in part due to poor diffraction efficiency. Calculations suggest that grating efficiencies in the region of <4dB should be attainable in optimised structures, and a total insersion loss of <6dB.

2.5 Performance Summary

The integrated spectrometer reported here displays the largest number of wavelength demultiplexed channels, the highest spectral resolution, and the lowest cross-talk for a monolothic wavelength demultiplexer, reported to date for an monoloithic device. The OMCVD growth and CAIBE grating formation, in conjunction with conventional photolithigraphy, have shown that they are capable of producing a device with a relatively large optical cavity (10mm x 1.6mm) without compromising the optical performance through material inhomogeneity or etch-wall imperfections. The particular device we have realised should be capable of operating with a channel throughput of 3-5Gb/s over 35 channels, yielding a total throughput capacity in excess of 100Gb/s.

3. USE OF THE SPECTROMETER IN WDM NETWORKS

As described in the introduction, passive multiplexers / demultiplexers are required for wavelength multiplexed networks such as Bellcore's generic LAMBDANET architecture shown in Figure 1 or the passive wavelength routing network illustated in Figure 2. Advanced wavelength cross-connect routing fabrics also call for small, rugged, wavelength multiplexers / demultiplexers.

The wavelength multiplexer / demultiplexer presented in this paper has the virtue of being a single component and of being compact. It does, however, have a high insersion loss. Several measures may be taken to reduce this and the lower limit of what might be attainable is currently under investigation. When the insersion loss of the semiconductor based device reaches that of an equivalently performing dielectric based device (which can be realised with a much lower insersion loss) then the virtues of compactness of the semiconductor device will assure its preferential use. Until that day, however, the dielectric based device must be prefered for use a passive multiuplexer or demultiplexer.

For the detection of multi-wavelength signals and the generation of multi-wavelength light, however, the InP-based device is ideal as it may be monolithically integrated with both laser sources and detectors.

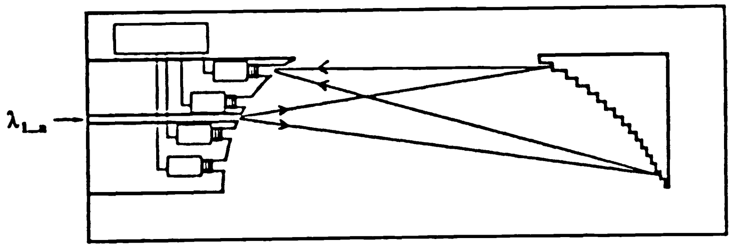

Figure 9. Proposed integrated WDM receiver chip.

A vision of a multi-wavelength receiver chip integrating the demultiplexing and detection functions is shown in Figure 9. The wavelength multiplexed signal is input into the device, as described above, but now the demultiplexed signals are incident on photodetectors integrated into the output waveguides. Such waveguide-integrated detectors are already under research, and one realisation is shown in Figure 10 [8]. This particular implementation employs an InGaAs metal-semiconductor-metal (MSM) detector which, being simple to fabricate and planar, is easily integrated with the waveguide and may also be readily integrated with FET-based receiver circuitry. MSM-FET receivers are currently being intensively researched for use in high bit-rate communications [9].

Lasers may also be combined monolithically with the optical cavity to provide a multi-wavelength source [10]. Indeed, it should be noted that the use of a common configuration for the optical cavity for the laser, the multiplexer / demultiplexer, and the receiver will assure that these three components are spectrally matched. This will be an extremely important feature for systems with a large number of remote wavelength selective nodes.

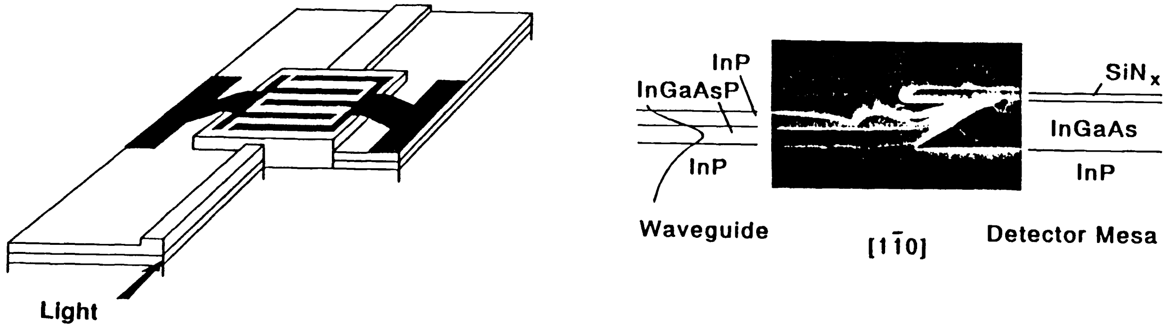

Figure 10. Example of a waveguide integrated photopdetector, in this case a planar metal-semiconductor-metal (MSM) InGaAs detector.

4. SUMMARY

We have descibed an InP-based wavelength multiplexer / demultiplexer and discussed its use in WDM systems. The InP spectrometer demultiplexes 78 channels with an inter-channel spacing of 1nm and is almost insensitive to the state of the incident polarization. The channels have a 0.3-0.35nm pass-band and a cross-talk of at least -19dB.

WDM systems employing integrated multiplexers/ demultiplexers, multi-wavelength transmitters and wavelength demultiplexed receivers have potentially a very significant role to play in the future of both telecommunications and high speed distributed computing. In this paper we present details of an InP-based integrated multiplexer / demultiplexer which may form the basis for the development of such devices.

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5. REFERENCES

1. C.A.Brackett, *J. Sel Areas in Comm.*, 8, 948, (1990).
2. N.R.Dono, P.E.Green Jr., K.Liu, R.Ramaswami, and F.F-K Tong, *J. Sel Areas in Comm.*, 8, 983, (1990).
3. M.S. Goodman, J.L. Gimlett, H. Kobrinski, M.P.Vecchi, and R.M, Bulley, J. Sel. Areas in Comm., 8, 995, (1990) . ™LAMBDANET is a trade mark of Bellcore.
4. S.S.Wagner, H.Kobrinski, T.J.Robe, H.L.Lemberg, and L.S.Smoot., *Conference Proceedings, GLOBECOM '88*, 1569, 1988.
5. H.A. Rowland, *Phil. Mag.*, 13, 467, (1882). *Ibid*, 35, 397, (1893).
6. J.B.D.Soole, A.Scherer, H.P.LeBlanc, N.C.Andreadakis, R. Bhat, and M.A. Koza, *Electronics Letters*, 27, 132, 1991.
7. A. Scherer, J.L.Jewell, Y.H.Lee, J.P.Harbison, and L.T.Florez, *Appl. Phys. Lett.*, 55, 2724, (1989).

8. J.B.D.Soole, H.Schumacher, R. Esagui, H.P. LeBlanc, R. Bhat, and M.A. Koza, *Appl. Phys. Lett.*, 55, 2173, (1989).
9. G.-K.Chang, W.-P.Hong, J.L.Gimlett, R.Bhat, C.K.Nguyen, G.Sasaki, and J.C.Young, *IEEE Photon Tech. Lett.*, 2, 197, 1990.
10. P.A. Kirkby, *J. Lightwave Tech.*, 8, 202, (1990).