Phased-array wavelength demultiplexer with flattened wavelength response

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theory, a second frequency where the coupler is perfectly matched
exists demonstrated a band slightly larger than one octave. Excellent
Acknowledgment: knowledge the smallest
ring CNET Lannion for his helpful suggestions.

Table 2: Coupler measured performances in frequency range 4.5 -
         9.2 GHz

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electrical definition</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return loss</td>
<td>( \text{mag}(S_{21}) )</td>
<td>(-20, \text{dB})</td>
</tr>
<tr>
<td>Transmission when fed to H-port</td>
<td>( \text{mag}(S_{11}) ), ( \text{mag}(S_{22}) )</td>
<td>(4.3 \pm 0.3, \text{dB})</td>
</tr>
<tr>
<td>Transmission when fed to E-port</td>
<td>( \text{mag}(S_{11}) ), ( \text{mag}(S_{22}) )</td>
<td>(4.3 \pm 0.3, \text{dB})</td>
</tr>
<tr>
<td>Output magnitude balance when fed to H-port</td>
<td>( \text{mag}(S_{11} / S_{33}) )</td>
<td>(0.3 \pm 0.05, \text{dB})</td>
</tr>
<tr>
<td>Output phase balance when fed to H-port</td>
<td>( \text{phas}(S_{11} / S_{33}) )</td>
<td>(0^\circ \pm 4^\circ)</td>
</tr>
<tr>
<td>Output magnitude balance when fed to E-port</td>
<td>( \text{mag}(S_{11} / S_{33}) )</td>
<td>(0.4 \pm 0.25, \text{dB})</td>
</tr>
<tr>
<td>Output phase balance when fed to E-port</td>
<td>( \text{phas}(S_{11} / S_{33}) )</td>
<td>(180^\circ \pm 4^\circ)</td>
</tr>
<tr>
<td>Isolation</td>
<td>( \text{mag}(S_{22}), \text{mag}(S_{33}) )</td>
<td>(-23, \text{dB})</td>
</tr>
</tbody>
</table>

Conclusion: We have presented a new small size, wideband hybrid
ring coupler. Its circumference is only 0.67\,\text{cm}, which is to our
knowledge the smallest size ever attained by a 180º ring hybrid.
All the coupler ports are fed by coplanar waveguides. The coupler
demonstrated a band slightly larger than one octave. Excellent
output magnitude and phase balance is achieved. The design sim-
plicity and the absence of any transition make the coupler suitable
for monolithic integration.

Acknowledgment: The authors wish to thank A. Boulouard from
CNET Lannion for his helpful suggestions.

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plexers [5]. Within a certain wavelength range, the focused spot in the image plane (Fig. 2) will couple efficiently to the output waveguide. Although the power distribution between these modes strongly depends on the relative position of the image, the total coupling efficiency will be close to 100%, as long as the image is not too close to the edge of the output waveguide.

![Fig. 2 Representation of image plane of demultiplexer](image)

Use of wide multimode output waveguides will flatten the spectral response of the demultiplexer.

Owing to the multimode excitation of the output waveguide, the demultiplexer outputs cannot be coupled efficiently to monomode output fibres. If they are however coupled to detectors, the advantage of the flattened response can be fully exploited.

A four-channel demultiplexer with 2 nm wavelength spacing at 1.54 μm has been designed. The array has 46 waveguides with a path length difference of 59 μm between adjacent arms. The radius of curvature in the array varies from 500 to 805 μm. The width of the input waveguides is 2.5 μm. At the output, 6 μm wide multimode output waveguides separated by a 3 μm gap are used. Calculations predict a 1 dB transmission bandwidth of 1.12 μm, taking into account that the highest order mode of the multimode output waveguide will be radiated out of the bend. A diffraction loss of 2 dB was allowed for the outermost receiver waveguides. Calculations predict a TE-TM shift of 4.1 nm due to waveguide birefringence. The total device size is 3.3 x 3.9 mm² including the input and output branches.

**Fabrication:** The demultiplexer is realised on InP substrate for integration with photodetectors. A double-heterostructure waveguide structure was grown by LPMOVPE: a 1.5 μm InP buffer layer, a 0.66 μm InGaAsP(1.3) waveguide core and a 0.32 μm InP top cladding. The demultiplexer was fabricated by etching 0.4 μm deep waveguide ridges using CH₄/He RIE with an SO₂ etching mask. In a second step the output waveguides were etched 1.5 μm deep waveguide ridges using CH₄/He RIE with an SO₂ etching mask. In a second step the output waveguides were etched another 60 nm to reduce the radiation loss of the bends. Finally the sample was cleaved and AR-coated by evaporation of an SiO₂ layer onto the waveguide facets.

**Results:** Light from an HP 8168A tunable laser source was end-fire coupled into the input waveguide using an N.A. = 0.65 microscope objective. The light emanating from the multimode output waveguide was imaged onto a Ge photodiode. The attenuation of 2 μm wide straight reference waveguides was found to be 2 dB/cm for both polarisations by Fabry-Perot contrast ratio measurements on uncoated waveguides. Fig. 3 shows the output power of the four receiver channels for TE-polarised light. Measurements are calibrated against straight reference waveguides. The excess loss of the device is 3.5 ± 4.5 dB with a crosstalk level below -18 dB. On-chip losses are estimated to be 4 ± 5 dB by adding the loss of a straight reference waveguide. The average 1 dB bandwidth is 1.05 nm. For the TM polarisation the spectrum is blue shifted 4.0 nm due to waveguide birefringence.

**Fig. 3 Spectral response of phasar demultiplexer**

Measurements are calibrated against straight reference waveguides.

**Discussion:** The insertion loss of this device is comparable to demultiplexers in InP that we realised before [3]. The measured 1 dB bandwidth agrees quite well with theoretical calculations. The crosstalk level is ~ -5 dB higher than for previous demultiplexers. This is mainly attributed to the wider output waveguides, that will pick up more of the incoherent background radiation that is due to local variations in the propagation constant in the array.

The realised 1 dB bandwidth in excess of 1 nm will relax the matching requirements for the laser source wavelength with respect to the transmission maximum of the demultiplexer. In addition this flattened wavelength response can be used for polarisation independent demultiplexers [6, 7] based on a TE-TM shift equal to the demultiplexer periodicity. In that case the flattened wavelength response will relax the required tight control of the TE-TM shift of such a device.

**Conclusions:** A four-channel phased array demultiplexer has been realised on InP substrate with a 1 dB bandwidth of 1 nm at 2 nm wavelength spacing. The on-chip loss of the device is 4 ± 5 dB with a crosstalk level below -18 dB. The flattened wavelength response will alleviate several tuning and trimming problems in WDM applications.

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M.R. Amersfoort, C.R. de Boer, F.P.G.M. van Ham and M.K. Smit (Delft University of Technology, Department of Electrical Engineering, PO Box 5031, 2600 GA Delft, The Netherlands)

P. Demeester (University of Gent/IMEC, Department of Information Technology, Belgium)

J.G.M. van der Tol (PTT Research, Leidsche Rijn, The Netherlands)

A. Kunte (Delft University of Technology, Department of Applied Physics, The Netherlands)

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20Gbit/s, 1.55μm strained-InGaAsP MQW modulator integrated DFB laser module

K. Wakisaka, K. Sato, I. Kotaka, M. Yamamoto and T. Kataoka

Indexing terms: Integrated optoelectronics, Electroabsorption modulators, Distributed feedback lasers

The high-speed (20Gbit/s) and highly efficient (2V peak to peak for a 22dB on-off ratio) operation of an MQW integrated electroabsorption modulator/DFB laser module is demonstrated. Output power from the module is over +3dBm in the gaged singlemode fibre. To the authors' knowledge, this is the first report of 20Gbit/s operation with a monolithically integrated light source.

Introduction: For long-haul optical fibre transmission over 100km at a wavelength of 1.55μm, chirpless or low-chirp light sources are required. An electroabsorption intensity modulator modulator monolithically integrated with a DFB or DBR laser is the most promising light source. Since an external modulator and a DFB laser diode (LD) were first integrated [1], many structures have been reported [2-9].

In high-speed systems with greater than 10Gbit/s capacity, the modulation voltage must be reduced to produce a drive voltage in high-speed IC drivers. Multiquantum well (MQW) structures based on the quantum-confined Stark effect are promising because of their highly efficient electroabsorption [4,5,9]. We reported the first successful 15 - 20Gbit/s 100km transmission experiments [10] using an ultrahigh-speed driveless InGaAs/InAlAs MQW intensity modulator with a small penalty of less than 1dB. However, the stability of the optical coupling between the fibre and the solitary modulator was a serious problem. Recently, we succeeded in fabricating a strained InGaAsP-MQW modulator integrated DFB laser operating at low driving voltage and high emitting power [9]. In this Letter, we report, for the first time, 20Gbit/s modulation using an integrated light source module with a low driving voltage of 2V.

Device structure and design: The chip structure is the same as reported in [9]. It has two kinds of MQW layer: one a laser active layer and the other an electroabsorption layer with photoluminescence wavelengths of 1.55 and 1.49μm, respectively. After fabricating first-order gratings on the top of the separate confinement heterostructure layer of the MQW LD and etching the LD section selectively, the modulator section was formed. The lengths of the modulator, the separation region and LD are 200, 50, and 300μm, respectively. An antireflection coating with lower than 0.5% reflectivity was deposited on the front of the modulator facet to eliminate residual reflection. To reduce device capacitance, polyimide was spin-coated under the bonding pad of the modulator.

The extinction ratio of the chip output power was 22dB at -2V and 30dB at -3V, at the coupled spherical end fibre. The 3dB bandwidth for a 50Ω load was more than 15GHz with a parasitic capacitance of only 0.5pF.

Module design: Optical transmitter modules for 10Gbit/s systems have been developed using a Franz-Keldysh electroabsorption modulator integrated light source [11]. In the module in this Letter, we reduced parasitic reactance caused by the assembly for high-speed modulation, introduced an efficient optical coupling scheme for high output power, and used an efficient compact optical isolator for low noise operation. Moreover, temperature controllability and a hermetically sealed package improve stability and reliability. To reduce the impedance mismatch between the monolithic chip and the transmission line, a thin film resistor of 50Ω was mounted close to the modulator chip. This matching circuit has a return loss of more than 10dB from 0 to 10GHz. The bonding wire between the chip and the line is designed as short as possible.

For efficient optical coupling of the chip to a singlemode fibre, we used an optical coupling scheme where a spherical lens with a 600μm diameter and one with a 2.0mm diameter were placed in a confocal arrangement to accommodate the optical isolator. The minimum coupling loss of this lens system was 4.0dB, including isolator loss.

To stabilize operation, we introduced a thermoelectric cooler. The module can be operated from 0 to 50°C with a stable temperature of 25±0.01°C. All elements except the isolator were permanently fixed by YAG laser welding.

Fig. 1 Output power against applied voltage from module at injection current of 100mA

Emitting wavelength is 1.546μm

Module performance: The output power from the module as a function of applied voltages is shown in Fig. 1. The average output power of the chip was +3dBm in the singlemode fibre. The threshold current of the DFB laser was 15mA.

The small signal frequency response is shown in Fig. 2. The injection current was 80mA and the DC applied voltage for the modulator was -0.4V. The -3dB electrical bandwidth of the transmitter module was more than 15GHz which was consistent with the measured capacitance. Large signal measurements were performed at 20GHz in a pseudorandom sequence 2-1 -1 pulses long with 2V non-return-to-zero (NRZ) modulation. The centre oscillation wavelengths and the full widths at 20dB down with and without modulation were 1.5466 and 1.5468μm, and 0.29 and 0.42nm, respectively. A sidemode suppression ratio of more than 40dB was obtained. The output power of the module was -0.7dBm under 20Gbit/s modulation and injection current of 85mA.

Fig. 2 Small signal frequency response of module

Injection current for laser diode is 80mA, and applied voltage for modulator is -0.4V

Fig. 3 shows the eye pattern for 20Gbit/s modulation driven by a 2.0V peak to peak electrical signal. A clear eye opening was