As with our earlier devices, the structures are ridge-guided optical waveguide rings formed in GaAlAs/GaAs double quantum well material. The ridge width is 2μm and the cavity lengths are 7.35 and 7mm. When the laser is at threshold, the cavity losses are compensated for by the gain and an optimum value of $k_2 = 0.5\%$ is found. The rings are placed one within another, lightly coupled by a directional coupler section (Fig. 2). The outer one is coupled via a multimode interference (MMI) coupler to a straight output waveguide. The MMI coupler is 6μm wide and 370μm long, and has been designed for a –3dB split ($k_1 = \sqrt{0.5}$). The directional coupler between the two resonant rings has a minimum waveguide separation of 4μm to give a much smaller coupling ratio; the design has been simulated by BPM, which gives $k_2 = 0.03$. The output waveguide is tilted at 5° to the cleaved sides of the substrate to reduce reflections back into the resonator. Separate contacts are made to the inner ring and to the outer ring.

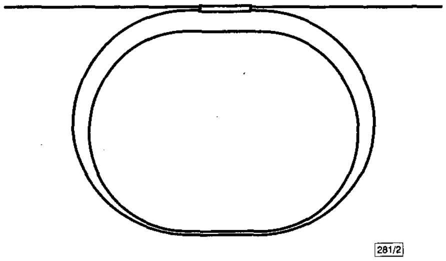

Fig. 2 *Layout of double-ring laser; inner and outer ring directionally coupled (weakly); MMI coupling to output waveguide*

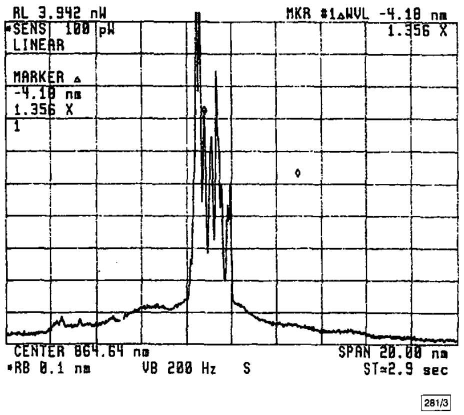

Fig. 3 *Double ring laser – output spectrum with* $I_{ext} = 900mA$ *and* $I_{int} = 0$

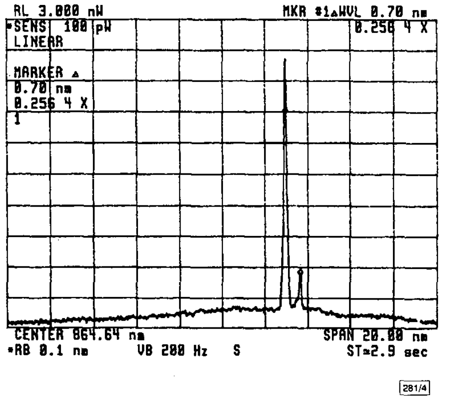

Fig. 4 *Double ring laser – output spectrum with* $I_{ext} = 900mA$ *and* $I_{int} = 900mA$

The devices have been tested by biasing the outer ring above threshold and observing how the biasing of the inner ring affects the output of the device. With a forward current of 900mA applied to the outer ring (1.5 times threshold), a multimode spectral output was observed, as in Fig. 3. By applying a forward bias to the inner ring and increasing the drive current by degrees, the multiple lasing resonances of the outer ring are gradually suppresses and are replaced with wider-spaced resonances, the frequency spacing of which corresponds to the free spectral range (FSR) of the two-ring resonant structure, as shown in Fig. 3 for an inner-ring drive current of 900mA. Two lasing modes are apparent here; the measured frequency separation of ~0.7nm is near to the calculated FSR of the double ring resonator of 0.64nm. The centre frequency of the spectrum has moved to a longer wavelength. We think this is because the inner, lower loss, ring cavity has a gain peak at a longer wavelength, due to a lower carrier density at threshold altering the refractive index.

The filter theory used to describe the coupled ring resonant circuit is linear, excluding saturation, and is of limited value when applied to the lasing structure, but confirms the experimental behaviour. The need for a small coupling ratio has been emphasised by numerical simulation based on the model of Lang and Kobayashi [4]. Dynamic behaviour ranging from self-pulsation to coherence collapse was found for a master-slave in-line semiconductor laser system [5], for which dynamically stable operation was only obtained with a coupling ratio < 1%. In that analysis the lasers were coupled through an isolator, although subsequent calculations on a similar system but omitting the isolator generated similar results. We plan to extend that dynamic analysis to the present case, to obtain a realistic model of the double-ring laser. Further designs of double-ring resonator are being fabricated, to be used either as passive transmission filters or as lasers. Operation outside the regimes of stability should be possible, where we hope to observe self-pulsation and coherence collapse.

14 July 1999
Electronics Letters Online No: 19991084
DOI: 10.1049/el:19991084

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Vertical coupler with separated inputs and outputs fabricated using double-sided process

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A novel vertical coupler used as a wavelength multiplexer with separated input and output waveguides is demonstrated. The wafer fusion technique enables both frontside and backside processing of the thin epitaxial films. A vertical coupler with a 4mm interaction region demonstrates 20nm wavelength spacing.

Introduction: Directional waveguide couplers are fundamental components in photonic integrated circuits used in optical communications systems. They can be used as optical switches, splitters, modulators and narrowband filters [1 – 4]. Conventional directional couplers are planar where the two waveguides are horizontally (laterally) arranged. One disadvantage of the planar design is that the spacing between two coupled waveguides is limited by the fabrication techniques. This results in long coupling lengths (around several millimetres) [1 – 3]. Vertical directional couplers, on the other hand, have a very short coupling length that is even smaller than 100μm [5], because the spacing between two vertically stacked waveguides can be reduced to < 0.5μm, and this can be precisely controlled by the material growth. However, the two input or output waveguides in vertical couplers are so close (< 1μm) together that the direct coupling of individual waveguides to fibres is very difficult. This has limited the practical applications of vertical couplers in fibre-optic systems. To solve this problem, recently a novel fused vertical coupler [6, 7] based on the wafer fusion technique [8] has been proposed where the two strongly coupled waveguides are fabricated on two different substrates and separated laterally.

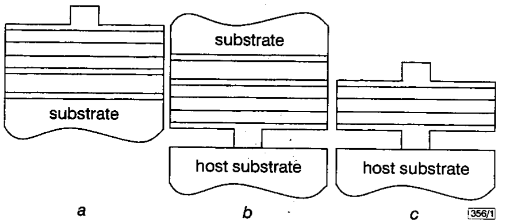

Fig. 1 *Coupler fabrication steps*

a Conventional processed epitaxial layer structure
b Epitaxial structure is inverted and bonded to another host substrate
c After removing original substrate, exposed backside of epitaxial structure is processed

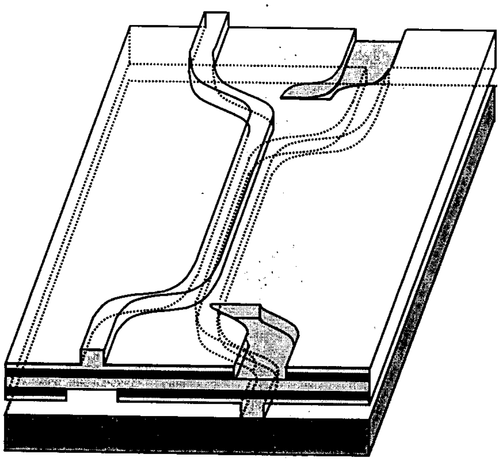

Fig. 2 *Schematic diagram of vertical coupler with separated inputs and outputs*

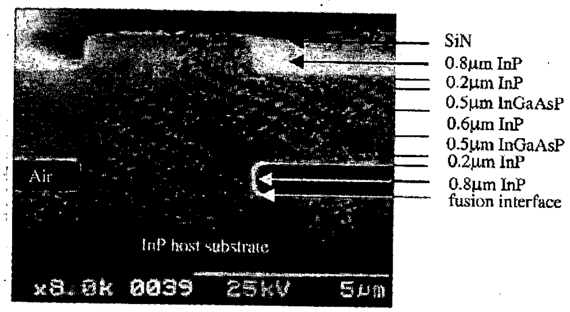

Fig. 3 *SEM picture of vertical coupler fused to InP substrate*

In this Letter, we demonstrate a vertical coupler with separated input and output waveguides fabricated using both frontside and backside processing of the same substrate. Using wafer fusion, a conventionally processed epitaxial layer structure (Fig. 1*a*) is inverted and bonded to a new host substrate (Fig. 1*b*). After removing the top substrate and leaving only the thin epitaxial film bonded to the host material, the exposed backside of the epitaxial structure can then be processed as well (Fig. 1*c*). This technique enables the fabrication of 3D photonic integrated circuits.

Experiments: The schematic drawing in Fig. 2 shows a vertical coupler with separated inputs and outputs, where the two waveguides are coupled vertically and separated horizontally in different planes. The device fabrication begins with a metal-organic chemical vapour deposition (MOCVD)-grown structure (Fig. 3), which includes a 0.8μm InP frontside ridge layer, a 15nm InGaAsP (bandgap 1.1μm) etching stop layer, a 0.2μm InP cap layer, a 0.5μm InGaAsP (bandgap 1.3μm) frontside guiding layer, a 0.6μm InP coupling layer, the same backside guiding, cap, etch stop and ridge layers, and finally a 0.2μm InGaAs for substrate removal on InP substrate. First, the 3μm width frontside ridge waveguides are formed by reactive ion etching (RIE) and chemical wet etching. The frontside guiding layer above the backside waveguide structure in non-coupling areas is removed by further wet etching. The waveguide sample is then inverted and fused to a bare InP substrate under pressure for 40min at 630°C. After removing the top substrate and InGaAs etch stop layer, the backside waveguides are fabricated and the unnecessary guiding layer above the frontside waveguide structure is removed as before. The waveguide alignment is facilitated using infrared photolithography.

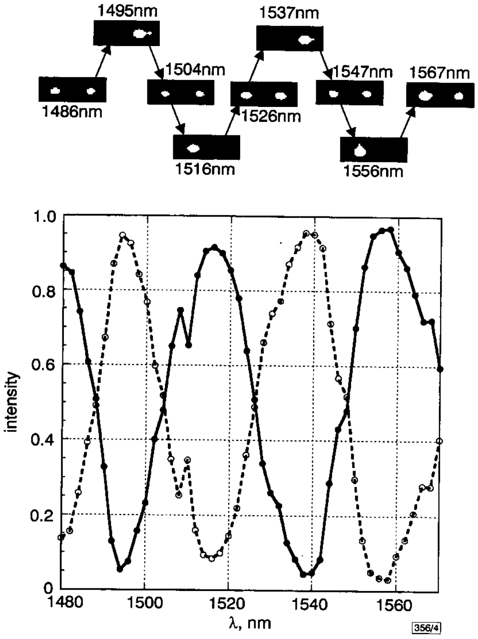

Fig. 4 *Light output intensity against wavelength*

– –○– – right waveguide
——●—— left waveguide
Near field images at outputs are also shown

Fig. 3 shows the SEM picture of the coupling region. In our former fused vertical couplers [6], the fused interface was between the two guiding layers. This introduced an excess optical loss due to imperfections at the non-epitaxial interface. To separate the input and output waveguides, it was necessary to align the two wafers with submicrometre resolution during the wafer fusion process. In our current work, the fused interface is not important since it is far away from the guiding layer. Also, no alignment is necessary during the fusion process.

Results and discussions: To characterise the device performance, light from a tunable laser was coupled to an input waveguide by a singlemode fibre. The light at the output was collected by another singlemode fibre which was connected to a detector. Fig. 4 shows the measured output light intensity as a function of wavelength. The near field images at the output were recorded by an IR camera with a lens and they are shown in Fig. 4. The total device length is 8mm, the coupler length is 4mm and the separation between two waveguides is 20μm. As we expected, the output intensity is a periodic function of wavelength and the oscillation period is ~40nm. This means that the device can be used as a wavelength multiplexer/demultiplexer for 20nm wavelength spacing. This small wavelength spacing is very difficult to achieve in a conventional horizontally arranged coupler because of the weak wavelength dependence of the coupling coefficient [9]. By cascading several strongly coupled vertical couplers together, multi-channel multiplexers with several-nanometre spacing can be realised.

It is worth noting that in the processing of both sides by the wafer fusion technique only one epi-wafer is needed and another host wafer can be of any material, such as Si, glass, etc. This will reduce the cost and give more flexibility for the fabrication of 3D photonic integrated circuits.

Conclusion: We have successfully realised a vertical coupler with separated input and output waveguides by using wafer fusion technology. This device can be used as a wavelength multiplexer in fibre-optic systems. 20nm channel spacing has been achieved for a vertical coupler with 4mm coupling region. Wafer fusion technology enables both frontside and backside processing of thin epitaxial films and is an important tool for realising novel devices and 3D photonic integrated circuits.

Acknowledgments: We would like to thank A.W. Jackson for many stimulating discussions. This research was supported by DARPA and AFOSR under the Multidisciplinary Optical Switching Technology (MOST) center.

19 July 1999

Electronics Letters Online No: 19991062

DOI: 10.1049/el:19991062

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Compact optoelectronic oscillator with ultra-low phase noise performance

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A compact optoelectronic oscillator (OEO) is presented which is using constructed using a DFB laser, a semiconductor Mach-Zehnder modulator, and a dielectric resonator based RF filter. The achieved phase noise is –50dBc/Hz at 10Hz and –130dBc/Hz at 10kHz from a 10GHz oscillation frequency, a performance comparable to that of an OEO constructed with a diode-pumped YAG laser and an $LiNbO_3$ modulator.

Introduction: Optoelectronic oscillators (OEOs) have the capability of achieving ultra-low phase noise for both microwave and optical communications [1]. The oscillation in an OEO is produced via a feedback loop which includes a modulator, an optical fibre delay element, and a photodetector. However, the previously demonstrated OEOs were constructed with expensive and bulky diode-pumped YAG lasers, $LiNbO_3$ modulators, and cavity RF filters. For communications, radar, and space applications, compact and low cost OEOs are preferred. We report in this Letter a compact and high performance OEOs constructed with an integrated module consisting of a DFB laser and a semiconductor modulator, and a dielectric resonator based RF filter. The experimental results demonstrate that low cost semiconductor lasers and modulators, together with low cost dielectric resonators, can be used to construct optoelectronic oscillators.

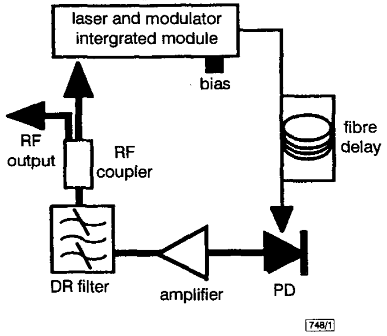

Fig. 1 *Configuration of compact OEO*

Configuration of compact OEO: The configuration of the compact 10GHz OEO is shown in Fig. 1. We used a DFB laser integrated with a semiconductor Mach-Zehnder modulator. The measured RIN (relative intensity noise) of the laser output is –110dBc/Hz at 10Hz and –135dBc/Hz at 10kHz, which sets a limit on the phase noise of the OEO.

The key to the low phase noise performance of an OEO is the long optical fibre loop delay. The highest spectral purity signals with the OEO are achieved with the longest fibre length [1]. Because the OEO is essentially a multimode device, with its mode spacing inversely proportional to the length of the fibre, achieving ultra-low phase noise requires a filter with narrow enough bandwidth to select a mode for operation at a single frequency. Although a multi-loop scheme can be used for singlemode selection [2], it increases the complexity and size of the OEO. In this Letter, we use an ultra-narrow-bandwidth filter constructed with a dielectric resonator (DR) for singlemode selection.

Dielectric-resonator-loaded high-Q narrowband filters can be designed to occupy a total volume only ~5% of that of a waveguide filter with an equivalent performance and their Q at room temperature can be as high as 10^4. In addition, the temperature coefficient of the filter is exceptionally low, down to ±1ppm/°C at room temperature [3]. We designed and fabricated such a filter by placing an 8.7mm × 4mm high dielectric constant ($\varepsilon_r = 30$) ceramic cylindrical disc at the centre of an aluminium cavity with a size three times that of the DR disc. Using a design tool based on the finite element method, we found that the $TE_{5,1,\delta}$ mode has a frequency of 10GHz, and more than 90% of the energy can be confined in the disc. To obtain optimum mode matching, a tiny wire loop probe was used for both mode excitation and coupling.