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# A Compact Nine-Channel Multiwavelength Laser

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P. J. A. Thijs, M. K. Smit, and B. H. Verbeek

*Abstract*— **A phased-array-based multiwavelength laser has been realized on a chip area of 3.5 × 2.5 mm$^2$. The device has nine channels, spaced at 400 GHz around a central wavelength of 1.55 $\mu$m. Its performance is characterized by a minimum threshold current of 101 mA, a maximum fiber-coupled power of 0.37 mW, and a linewidth of 21 MHz. In addition, simultaneous four-channel operation is demonstrated.**

## I. INTRODUCTION

TO INCREASE the bandwidth and flexibility, the next generation of broadband optical communication systems are most likely to employ wavelength division multiplexing (WDM) techniques. In such systems, single laser sources which can be operated at several independent wavelengths simultaneuously will be attractive components [1]. A potential cost reduction, as compared to the wavelength selection and packaging of a number of discrete devices, is one of the main arguments used in favor of multiwavelength lasers.

So far, two approaches have been followed to realize such devices. The first one employs a laser array to independently generate the wavelengths, which are subsequently combined into a single output using an integrated star coupler [2], [3]. A disadvantage of this approach is the inherently low output power resulting from the use of such a coupler. The second approach uses a wavelength-selective element within the laser cavity, such as an etched grating [4] or a phased-array wavelength demultiplexer [5], [6]. Due to the relatively small index contrast of the QW-loaded [5] or selective-area epitaxy-grown embedded waveguides [6], these devices have a relatively large size (10 × 4 mm$^2$).

In this work, a compact nine-channel phased-array (PHASAR) based multiwavelength laser is presented. In order to obtain a small device size, it is fabricated employing an all-ridge waveguide structure with a high-index contrast.

## II. DESIGN AND FABRICATION

The wavelength selective element in the cavity is an 11 × 1 PHASAR having 50 waveguides with a minimum bending radius of 500 $\mu$m. It has been designed for operation around a central wavelength of 1.55 $\mu$m, with a 400 GHz channel spacing, and a 38.75-nm free spectral range. The inner nine input waveguides are fit with 500-$\mu$m-long amplifier sections, while the outer two arms are used for testing purposes. To avoid crosstalk due to cross-gain modulation, no amplifier section is employed in the common output port, in contrast to the devices presented in [5] and [6]. The cavity length is approximately 6 mm, with 0.9 mm length difference between the longest and shortest channels. Total device size is only 3.5 × 2.5 mm$^2$.

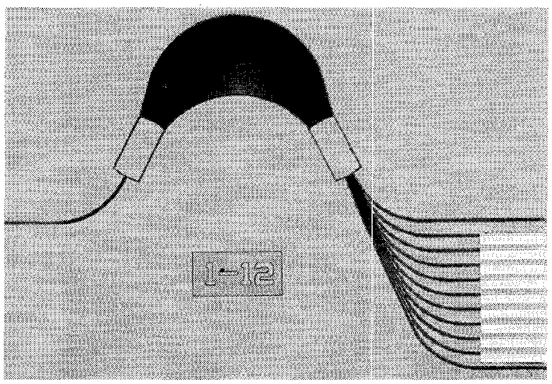

Fig. 1. Photograph of the device. Full size is 3.5 × 2.5 mm$^2$.

The ridge waveguide design results in a simple fabrication scheme comprising three low-pressure OMVPE epitaxial growth steps. Starting with a n-InP substrate, first a 120-nm-thick InGaAsP laser active layer with a bandgap wavelength $\lambda_{\text{gap}} = 1.55$ $\mu$m is fabricated. Next, a butt joint is made to a 230-nm-thick, $\lambda_{\text{gap}} = 1.3$-$\mu$m InGaAsP guiding layer in the passive part of the cavity. To keep device fabrication as simple as possible, the whole structure is covered with a 1.4-$\mu$m-thick p-InP cladding layer. Reactive ion etching (RIE) is subsequently used to define 2.5-$\mu$m wide, 1.35-$\mu$m high ridge waveguides. Finally, the amplifier contact metallization is fabricated and a 95% reflective coating is applied to the rear facet; the front facet is left as cleaved. In Fig. 1, a photograph of the finished device is shown. For characterization, chips are mounted epi-side up on copper carriers, providing eight leads for electrical contacts.

## III. EXPERIMENTAL RESULTS

In Fig. 2, the *L–I* characteristics of the eight addressable channels, measured at the common output port, are shown at a device temperature of 16 °C. For these and subsequent measurements, the CW light has been coupled into a lensed single-mode fiber. Clearly, some marked differences exist between the various curves. The threshold current ranges from 101 mA for channel 4 up to 122 mA for channel 1, while the maximum fiber-coupled power varies between 0.09

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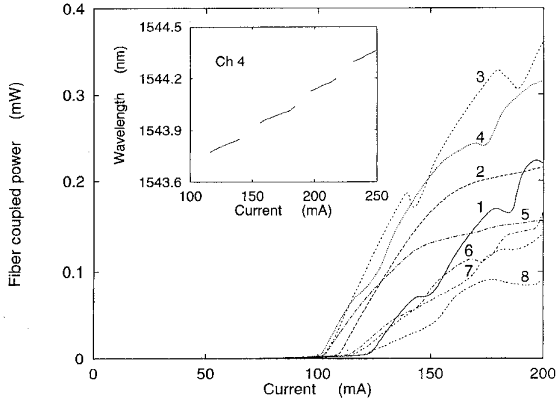

Fig. 2. *L–I* characteristics of the adressable channels. Inset: $\lambda$–*I* characteristic of channel 4.

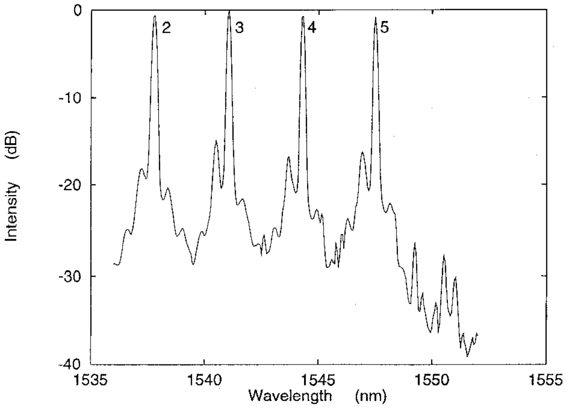

Fig. 4. Simultaneous four-channel operation at 11 °C.

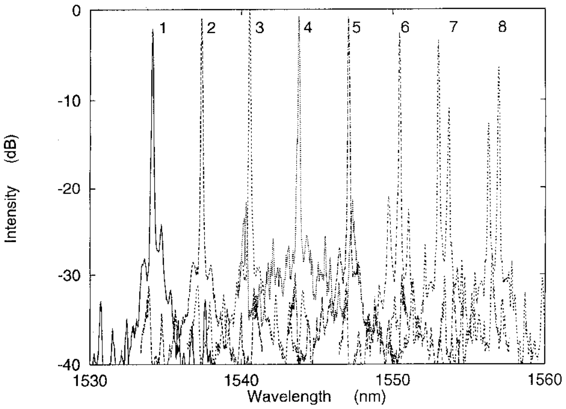

Fig. 3. Spectra at 10 mA above threshold, relative to the strongest channel.

mW for channel 8 and 0.37 mW for channel 3. In addition, the curves exhibit a number of kinks. These kinks coincide with hops among neighboring Fabry–Perot modes that fit within the passband of a single PHASAR channel, as has been verified with measurements of the wavelength-versus-bias current using a Michelson interferometer. For channel 4, this is shown in the inset of Fig. 2. Here, stable operation is found in four modes, spaced by approximately 0.06 nm, which is in agreement with the total cavity length of 6 mm. In between these modes, single-mode operation could not be obtained.

In Fig. 3, the spectra of the individual channels are shown at an operating current of 10 mA above threshold. Single-mode operation is obtained for channels 1–6, with a side-mode suppression ratio better than 15 dB. Channels 1–5 deviate less than 10 GHz from the 400-GHz channel spacing. Finally, at this operating current, a linewidth of 21 MHz has been obtained using a delayed self-homodyne technique. For the latter measurement, 60-dB isolation and antireflection coated optics were used to couple the light into the fiber. The measured value is in reasonable agreement with what one would expect for a device with the current characteristics.

If the spectrum is measured over a range wider than twice the free spectral range, spontaneous emission peaks can be observed at the next higher and lower order pass bands of the PHASAR. However, for the spectra shown in Fig. 3, the power level in those regions is about 20 dB and 35dB, respectively, down with respect to the lasing peaks.

Finally, in Fig. 4, the CW spectrum is shown when simultaneously biasing four adjacent channels of the device. The width of the peaks in this figure results from the 0.1-nm resolution of the optical spectrum analyzer used for the measurement.

## IV. DISCUSSION

To characterize the performance of the PHASAR multiplexer, one of the devices had the gain sections cleaved off, and transmission measurements were made using two lensed fibers. The fiber-to-fiber insertion loss of the best channel was 24.7 dB, with a crosstalk of less than −20 dB and a 3-dB filter bandwidth of 1.7 nm [7]. From the results of Fabry–Perot contrast measurements on straight waveguides, a waveguide loss of 20 dB/cm is estimated, accounting for the rather high insertion loss. This is attributed to the p-InP cladding layer which, for simplicity of processing, was grown over the entire device.

The high waveguide loss also is responsible for the high-threshold currents. Discrete laser arrays, consisting of the 500-$\mu$m-long gain sections without integrated passive waveguides, uniformly exhibit threshold currents of 38 mA at 20 °C. Similar arrays integrated with 500-$\mu$m passive waveguide sections yield in an increase of the threshold current to 45 mA.

To assess the quality of the (butt joint) amplifier-waveguide interface, the spectrum emitted at the rear facet (amplifier side) has been investigated. Measurements have been performed using an uncoated device at 175 mA bias current.The low (1.2 dB) gain ripple observed in the spectrum, which is due to spurious reflections off this interface, indicates a high quality of the interface.

In Fig. 5, the threshold current is given as a function of channel number, the drawn line serving as a guide to the eye. A nearly parabolic shape is observed for the first six channels, whereas the last two (doubly moded) channels clearly deviate from this trend. This effect is attributed to the angular insertion

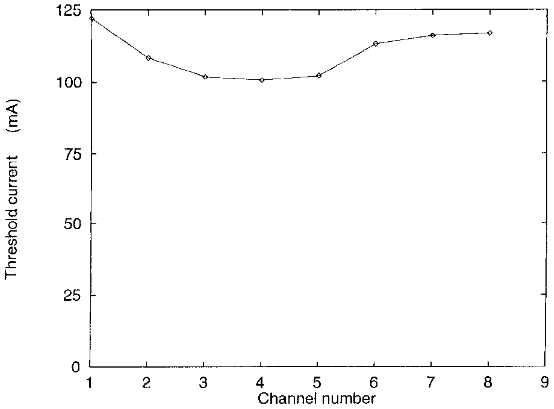

Fig. 5. Threshold current versus channel number.

loss[1] of the PHASAR, which is 2 dB by design. The fact that the minimum loss is not obtained for the central channel can be explained by the relatively large waveguide loss in combination with the increasing cavity length with increasing channel number.

A major improvement in device performance is expected from the use of undoped InP as a cladding layer of the passive waveguide, as opposed to the currently used p-InP.

## V. CONCLUSION

A multiwavelength laser based on the monolithic integration of a phased array with nine gain blocks has been fabricated and characterized. Due to the high-index contrast of the simple ridge waveguide structure, a compact design has been obtained, taking up a chip area of only 3.5 × 2.5 $\mathrm{mm}^2$. The device exhibits stable single-mode operation at six out of nine discrete wavelengths spaced by 400 GHz. Finally, simultaneous operation at four independently lasing channels has been demonstrated.

## ACKNOWLEDGMENT

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[1] The angular insertion loss is the additional loss that the outer channels experience relative to the central channel.