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Comparison of integrated multi-wavelength and (widely) tunable edge-emitting laser diodes

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Abstract. We present a thorough comparison of the characteristics of both tunable and multi-wavelength edge-emitting laser diodes. Both devices are currently seen as the most promising transmitters for future wavelength division multiplexing systems and networks. In our comparison, considerable attention is therefore paid to characteristics such as channel spacing and maximum number of channels and to frequency accuracy. Cost, stability and ease of use are other aspects which have been given attention, although they are not easily quantified. Because of their compactness and robustness, we only consider integrated devices.

Key words: laser diodes, wavelength selection, wavelength tuning, WDM sources

1. Introduction

It is expected that the ever-increasing traffic demands in telecommunication will soon require datastreams of Terabit/s over single optical fibres. Wavelength division multiplexing (WDM) is generally considered as the technique that will enable the future Tbit/s optical networks that will be formed by such optical fibres. At present, this kind of multiplexing is already used in point-to-point links with individual distributed feedback (DFB) lasers, emitting at different ITU wavelengths, being used as transmitters for the different WDM channels. For the near future, all-optical WDM networks are envisaged in which wavelength dependent routing will be done optically.

For both WDM point-to-point links and WDM networks, there are a number of potential advantages that could be brought along by the introduction of (widely) tunable and multi-wavelength lasers. Indeed, the use of tunable or multi-wavelength lasers as back-up sources will imply significant savings in inventory costs since only one back-up laser will be needed for all WDM channels instead of one back-up laser for each singular wavelength channel. This holds for both networks and point-to-point links, but becomes more significant in the case of networks where optical routing is implemented, for example using optical cross-connects or other routing elements.

In this last case, the alternative of using redundant channels for the back-up function will require that at least one other node is re-configured. This in turn obviously would complicate the network management significantly. Another potential advantage of tunable or multi-wavelength lasers is that new routing and switching mechanisms in networks can be introduced.

Both options, tunable and multi-wavelength lasers, have their own advantages and disadvantages. In fact, a possible preference for either type will certainly also depend on the channel spacing and the number of channels for which a WDM system is designed. There is at present however little agreement on these numbers for future systems and systems with a moderate channel count (e.g. 16) will probably co-exist with higher capacity systems with large channel counts of 100 or more. Both transmitter types have been investigated in the framework of the ACTS program. This paper on their comparison follows from the authors' participation in two such projects, AC329-ACTUAL which had the application and control of widely tunable laser diodes as subject, and AC332-APEX, which included work on multi-wavelength laser diodes.

Widely tunable and multi-wavelength laser diodes also come in many different varieties. It is not our aim to give a complete account of all possible tunable laser diodes and all possible multi-wavelength laser diodes, just to compare the main tunable and main multi-wavelength lasers mutually. For a more exhaustive overview of tunable and multi-wavelength laser diodes, the reader is referred to Amann and Buus (1998). We will focus on those laser diode types (tunable or multi-wavelength) that are currently regarded as the best options because of cost and size considerations, ease of use and stability and/or tuning speed. For what concerns the tunable laser diodes, the emphasis is on widely tunable laser diodes with a tuning range that covers the entire EDFA window (40 nm), although we will also discuss three-section DFB and distributed Bragg reflector (DBR) lasers with tuning ranges in the vicinity of 15 nm. As a matter of fact, these three-section DBR lasers (Delorme *et al.* 1995) and multi-section DFB lasers (Hong *et al.* 1999) can be very interesting candidates if the number of WDM channels is not very large or the total wavelength range covered by all channels is below 15 nm. In addition, their wavelength range is comparable to that of many multi-wavelength sources. Apart from these edge-emitting tunable laser diodes, also vertical cavity surface emitting lasers (VCSELs) with tunable emission wavelength are emerging (Vail *et al.* 1996; Vakshoori *et al.* 1999). They can give tuning ranges of 50 nm based on a movable top mirror formed as micro-electro-mechanical system (MEMS). Here we concentrate on the edge-emitting devices only however.

This paper starts with a separate description of the performance of both options. A significant amount of research on both tunable and multi-wavelength laser diodes has been done in recent years, which has resulted in a number of excellent characteristics. In paragraph 2, the state-of-the-art characteristics of widely tunable lasers are given and in paragraph 3 the same is done for multi-wavelength laser diodes. A more comparative study then follows in paragraph 4, which includes the potential advantages and disadvantages of both options from an application and economic point of view.

2. Performance of state-of-the-art widely tunable lasers

2.1. TYPES OF WIDELY TUNABLE LASERS

Nearly all tunable laser diodes for optical communication are based on multi-section DFB and DBR lasers. Multi-section DFB lasers consist of several (e.g. 3) active sections, separately pumped and each containing a diffraction grating (with possibly a different period for the different sections). DBR-laser diodes are shown schematically in Fig. 1 and have passive phase and Bragg sections. The tuning ranges for such laser diodes with three sections are typically anywhere in the range from 1 to 15 nm. Common to all these lasers is that the wavelength tuning is proportional to the variation of the mode refractive index of the laser waveguide with current or with temperature, which limits the tuning range.

Several improved designs have been proposed to overcome this limitation. One method is to use vertical co-directional couplers inside the laser as an intracavity filter. This filter is widely tunable but consequently poorly selective. Examples of this kind of laser are the vertical coupler laser (Alferness *et al.* 1992) and the ACA laser (Amann and Illek 1993). To improve mode selectivity, an extra filtering mechanism can be added. The grating coupler sampled reflector (GCSR) laser (Willems *et al.* 1992; Oberg *et al.* 1993), shown schematically in Fig. 2, combines a vertical co-directional coupler with a sampled grating DBR (SG-DBR) or a super structure grating DBR (SSG-DBR). These gratings exhibit a comb-shaped reflectivity spectrum, i.e. with a number of reflection peaks at regular frequency intervals. The broadly tunable, but poorly selective coupler filter is used to select one of the reflectivity peaks of the (S)SG-DBR, which in turn supplies sufficient mode selectivity. By injecting current into the (S)SG-DBR section, the reflectivity

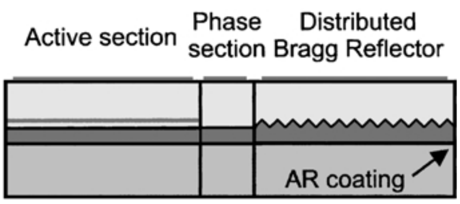


Fig. 1. Schematic of a three-section DBR laser.

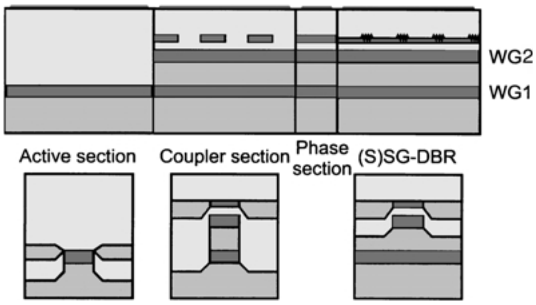


Fig. 2. Schematic of a GCSR laser.

peak can be tuned across a number of cavity modes, just as in a conventional DBR laser. The phase section allows continuous tuning of the cavity modes.

Wide tunability can also be achieved with a double-sided DBR with SG or SSG reflectors at both ends (Jayaraman *et al.* 1993; Ishii *et al.* 1996a, b). If the peak spacing of both reflectors is slightly different, lasing will be obtained where two peaks coincide. Only a relatively small tuning of one of the reflectors is required to make two other peaks coincide and get a large frequency change (coarse tuning). By tuning both reflectors simultaneously, the laser can be tuned across a number of cavity modes (medium tuning). Fig. 3 shows the structure, the reflectivity spectra and a measured wavelength vs. tuning current characteristic of an SSG-DBR laser.

For both the GCSR and the SSG-DBR laser total tuning ranges exceeding 100 nm have been achieved, and complete wavelength coverage over the whole EDFA window (40 nm) has been demonstrated (Rigole *et al.* 1996). Direct modulation at 2.5 Gbit/s has been reported, as well as switching times below 10 ns.

Other widely tunable lasers are various kinds of Y-lasers (Kuznetsov 1993; Kuznetsov *et al.* 1994) and external cavity lasers (Wyatt and Devlin 1983).

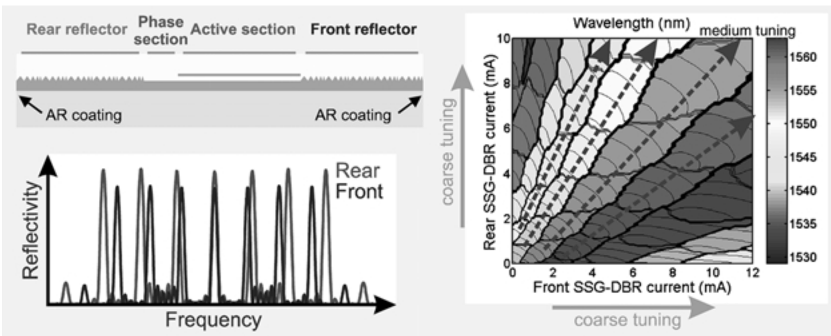


Fig. 3. Schematic of a SSG-DBR laser, with reflectivity spectra and measured wavelength tuning characteristic (as a function of the reflector currents).

Y-lasers have two or three lasing cavities with different lengths formed by a Y-branch from a common waveguide. By controlling the index in the different branches separately, tuning is obtained. The sections are normally all active. Common problems are poor side-mode rejection and complicated and critical wavelength control. Tunable laser diodes with an external cavity on the other hand can give very good characteristics but have a poor mechanical and thermal stability.

2.2. OPERATING CHARACTERISTICS

Table 1 summarises some typical characteristics of the DBR laser, the three-section DFB laser, the GCSR laser and the SG-DBR, and SSG-DBR lasers.

2.2.1. *Number of channels*

Since the lasers are continuously tunable, in principle any frequency within the tuning range can be addressed. The maximum quasi-continuous tuning ranges that have been demonstrated for GCSR, SG-DBR and SSG-DBR lasers are on the order of 60 nm. This however entails some trade-offs with respect to other parameters, e.g. power uniformity. Therefore, the tuning range is commonly limited to approximately 40 nm (EDFA window). Within a given tuning range, the number of channels is limited by the accuracy with which the frequency can be set. Over 100 channels at 50 GHz spacing have been demonstrated for GCSR, SG-DBR and SSG-DBR lasers (Sarlet *et al.* 2000a, b).

2.2.2. *Channel spacing – absolute wavelength accuracy*

As mentioned above, the channel spacing is limited by the obtainable frequency accuracy. Typically, one allows a ±10% deviation from the channel grid. With open-loop control frequency errors significantly less than ±5 GHz have been demonstrated, which means that a 50 GHz spacing is certainly feasible (Sarlet *et al.* 2000a, b). With feedback control, even better accuracies (±0.5 GHz) have been obtained (Ishii *et al.* 1998; Farrell *et al.*

Table 1. Comparison of the typical characteristics of the main tunable laser diodes considered in this paper

	3S-DBR[a]	3S-DFB[b]	SSG-DBR[c]	SG-DBR[c]	GCSR[c]	VCSEL[d]
Tuning range	15 nm	15 nm	40 nm	40 nm	40 nm	50 nm
SMSR	>40 dB	>55 dB	>35 dB	>40 dB	>30 dB	>50 dB
Maximum output power	5 mW Ex-facet	3 mW In fibre	5 mW In fibre	1 mW In fibre	3 mW In fibre	2 mW Ex-facet
Power uniformity	5 dB	2 dB	7 dB	5 dB	3 dB	Very high

[a] Delorme *et al.* 1995; [b] Hong *et al.* 1999; [c] Robbins *et al.* 1998; [d] Vakshoori *et al.* 1999.

1999; Sarlet *et al.* 1999), such that eventually the channel spacing could be reduced to 10 GHz or less.

2.2.3. *Threshold current and output power*
In these tunable lasers, the threshold current and output power at constant active section current tend to vary significantly across the tuning range due to the carrier-induced losses in the passive sections. For the SSG-DBR the threshold current varies between 5 and 15 mA, whereas for the SG-DBR and GCSR lasers values between 15 and 30 mA are obtained. The lower threshold values for the SSG-DBR laser are explained by the higher reflectivity values of the SSG-DBR mirrors (higher effective coupling coefficient) as compared to the SG-DBR reflectors in the other two laser types. The maximum output power is on the order of 1–5 mW in fibre. In the SG-DBR and SSG-DBR lasers, output power varies by as much as 5 dB across the tuning range (AC329-ACTUAL 1999). The GCSR laser has lower output power variation, about 3 dB, as in this device the light is directly emitted from the active section and does not have to pass through a passive DBR reflector with its associated carrier-induced loss. The three-section lasers and especially the three-section DFB laser seem to have an even better power uniformity, e.g. the power variation is less than 2 dB for the laser presented in Hong *et al.* (1999).

2.2.4. *Side-mode suppression ratio(SMSR)/ASE noise suppression/longitudinal mode stability*
For telecom applications, typically a SMSR of at least 30 dB is required. All tunable lasers considered meet this condition in ‘good’ operation points. For the GCSR laser typical SMSR values are between 30 and 35 dB, whereas for the SG-DBR and SSG-DBR laser the SMSR is at least 35 dB and generally over 40 dB (AC329-ACTUAL 1999). Similar numbers can also be obtained with three-section tunable laser diodes (Delorme *et al.* 1995; Hong *et al.* 1999). Feedback control schemes have been demonstrated on SG-DBR and SSG-DBR lasers, which keep the laser in a ‘good’ operation point and thus maintain a high SMSR (Ishii *et al.* 1998; Farrell *et al.* 1999; Sarlet *et al.* 1999).

2.2.5. *Modulation characteristics*
The intrinsic modulation characteristics of the lasers have been studied through relative intensity noise (RIN) measurements. For each laser, RIN has been measured as a function of active section current at a number of operation points (ITU channels). From the measurements, the *K*-factor was derived to predict the theoretical maximum modulation bandwidth. For both the SSG-DBR and the SG-DBR laser, this bandwidth is over 10 GHz for all the considered channels. Fig. 4 shows the maximum modulation bandwidth of an

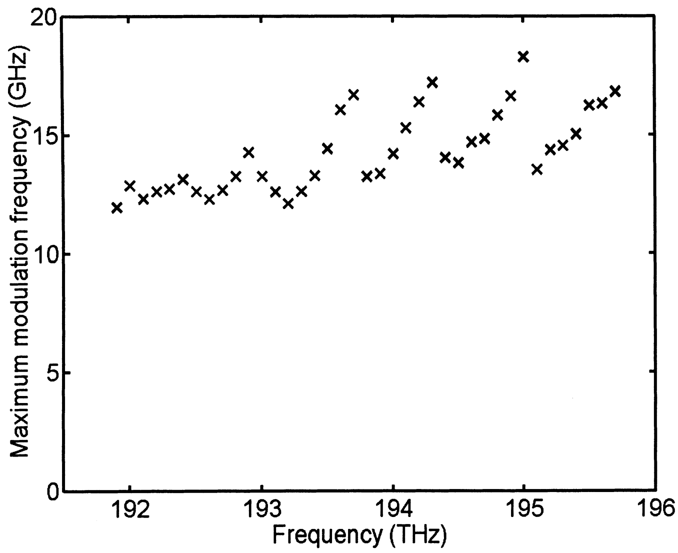


Fig. 4. Maximum modulation frequency as derived from RIN measurements for an SSG-DBR laser at 39 ITU channels between 191.9 and 195.7 THz.

SSG-DBR laser, derived from RIN measurements, at 39 ITU channels between 191.9 and 195.7 THz. For the GCSR laser, slightly lower values (8–9 GHz) were obtained for a small number of channels, as can be seen in Fig. 5 (Sarlet *et al.* 2000a, b). Values for the maximum modulation frequency of

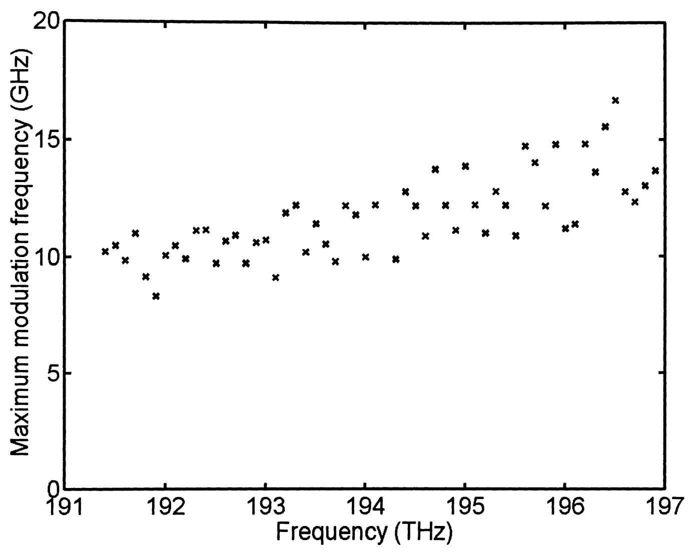


Fig. 5. Maximum modulation frequency as derived from RIN measurements for an GCSR laser at 56 ITU channels between 191.4 and 196.9 THz.

three-section tunable lasers have not been published, but on physical grounds can be expected to be at least similar to those of the four-section lasers.

2.2.6. *Laser linewidth*

The linewidth of four-section widely tunable laser diodes is reported to be similar to that of three-section DBR lasers (Ishii *et al.* 1996a, b). By choosing the tuning currents appropriately, linewidths below 100 MHz, sufficiently for currently envisaged WDM systems, can generally be obtained over a significant tuning range. Linewidths below 10 MHz over the entire 15 nm tuning range have been reported for the three-section DFB lasers (Hong *et al.* 1999).

2.2.7. *Control and reliability*

A lot of work has been reported on the control of DBR lasers and widely tunable DBR lasers (Ishii *et al.* 1998; Farrell *et al.* 1999; Sarlet *et al.* 1999, 2000a, b). Two types of control have been considered: look-up table control and feedback based control. For look-up table control, a table of tuning currents for all required frequency channels is generated. Since long characterisation times contribute considerably to the price of the widely tunable transmitters, a significant effort has been devoted to the reduction of the characterisation time. Also in cases where testing for ageing effects and e.g. recalibration are required it will generally not be permitted to have long interruptions of the system and fast recalibration is therefore a must. Currently, characterisation times (i.e. times required to generate the look-up tables) for four-section devices are on the order of 30 min and frequency errors are less than ± 1 GHz (Sarlet *et al.* 2000a, b). One technique to improve characterisation time is to replace as many time-consuming wavelength measurements as possible by much faster power measurements. For this purpose, optical filters can be introduced into the measurement set-up.

Feedback based control consists of corrections on the tuning currents based on real-time measurements. For feedback control of SG-DBR and SSG-DBR lasers, two mode stabilisation methods were developed: a method based on optical power monitoring (Ishii *et al.* 1998) and a method based on the active section voltage monitoring (Sarlet *et al.* 2000a, b). The methods rely on the appearance of saddle points and mimima respectively in the optical power and the active section voltage respectively as a function of the grating section currents at those points where the side-mode suppression is maximal. When these mode stabilisation schemes are combined with a frequency control loop that uses an optical reference filter, excellent frequency and mode stability are obtained: frequency errors less than ± 0.5 GHz and SMSR values above 35 dB have been demonstrated. Figs. 6 and 7 illustrate the performance obtained with feedback based control using measurement of the active section voltage, the optical frequency and the output power.

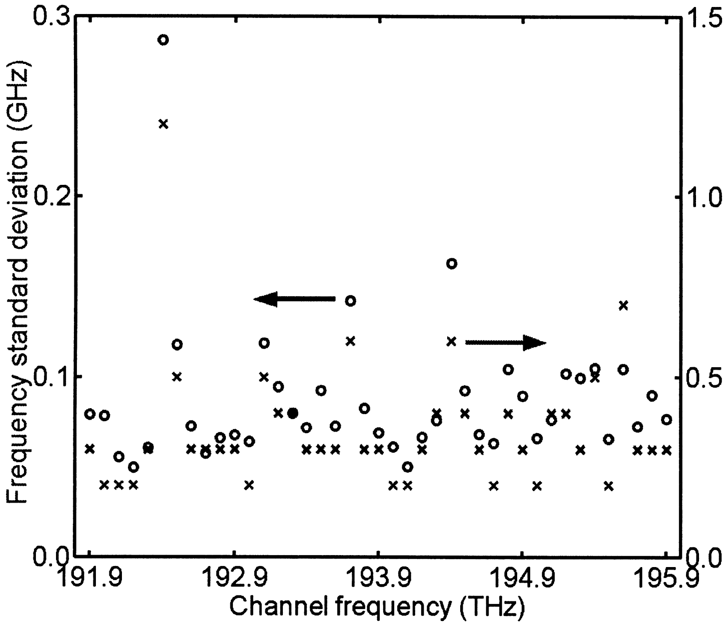


Fig. 6. Frequency standard deviation and maximum frequency variation (peak to peak) for 41 channels during a temperature sweep from 20 to 30 °C.

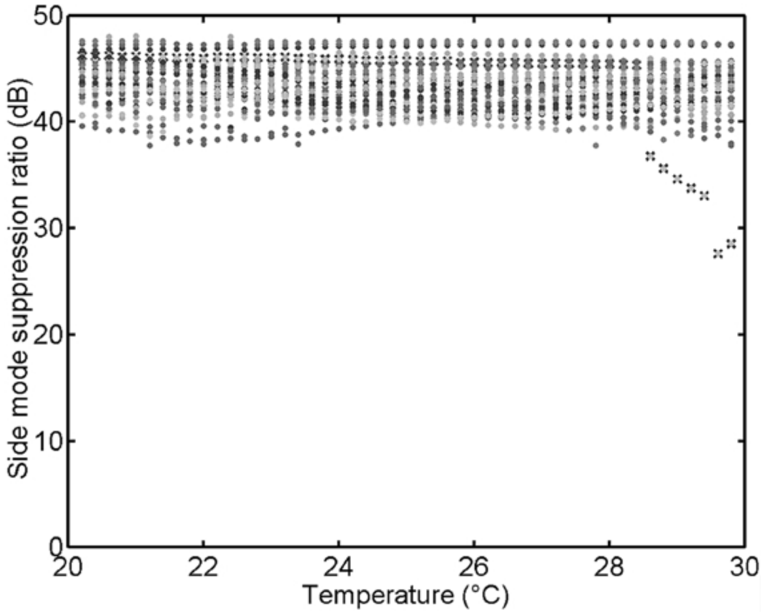
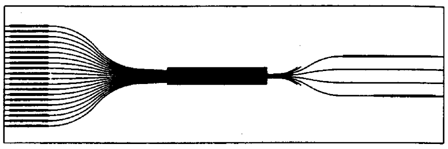


Fig. 7. Variation of SMSR for 41 ITU channels during a temperature sweep from 20 to 30 °C. Crosses (×) indicate the worst case channel at 192.4 THz.

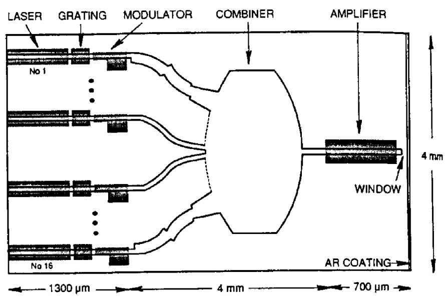
3. Performance of state-of-the-art multi-wavelength lasers

3.1. TYPES OF MULTI-WAVELENGTH LASER DIODES

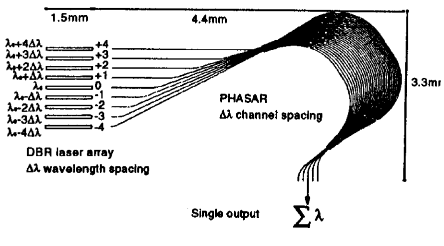
Multi-wavelength sources can be divided in two main classes: short-cavity laser arrays integrated with an extra-cavity combiner and long-cavity arrays with an intra-cavity multiplexer. Short-cavity laser arrays are realised by integrating a laser array and a passive combiner. Both DFB- and DBR-laser arrays are used. DFB lasers show an excellent side-mode suppression and high reliability (Zah *et al.* 1997). The lasing wavelength is quite stable (0.1 nm over the lifetime of the device). DBR-laser arrays, on the other hand, provide a more flexible wavelength allocation due to their tunability (Young *et al.* 1993; Menezo *et al.* 1999; Talneau *et al.* 1999). In most cases the combiner is a star coupler or a cascade of Y-junctions, both showing a $1/N$ splitting loss. In a few cases, also a phased-array demultiplexer was used, which becomes interesting for a high number of wavelengths (Menezo *et al.* 1999). To compensate for the splitting losses, an SOA can be integrated on the same chip. High-speed modulation may be obtained by integrating a modulator with each laser. Fig. 8 provides an overview of some relevant realisations.



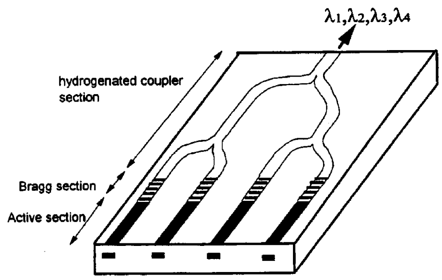
a. DFB-laser array with star coupler (Zah et al. 1997)



b. DBR-laser array with star coupler and integrated modulators (Young et al. 1993)



c. DBR-laser array with demultiplexer (Menezo et al. 1999)

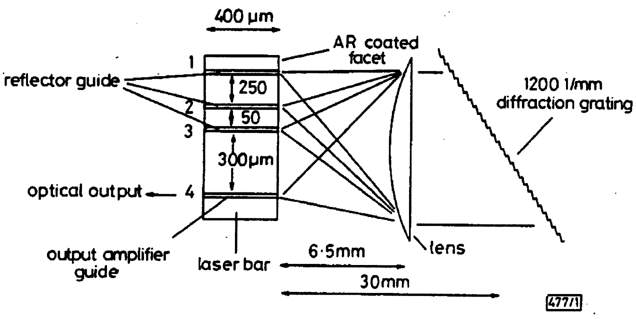


d. DBR-laser array with cascade of Y-junctions (Talneau et al. 1999)

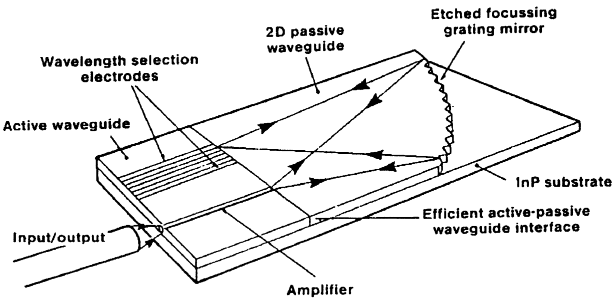
Fig. 8. Overview of multi-wavelength lasers realised by integration of an array of short-cavity lasers and a combiner.

The main advantage of these short-cavity laser arrays compared to other laser arrays is that each channel separately can be directly modulated at high speed. Arrays of DBR lasers have the additional advantage that they are more

(a) MGC laser



(b) MAGIC laser



(c) PAL in reflective configuration

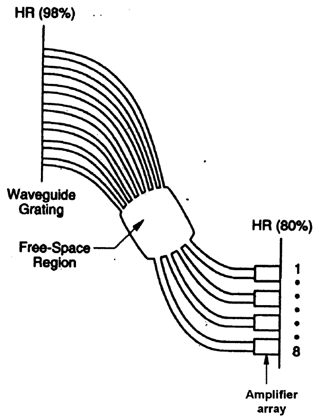


Fig. 9. Multiplexer used in a reflective configuration.

flexible due to the tunability of the DBR lasers. Disadvantages are the intrinsic $1/N$ loss in the combiner with N the number of wavelengths and the difficulties in getting accurate channel spacings and channel frequencies since the individual laser diodes can no longer be fine-tuned by changing the device temperature. If DBR-laser diodes are used, their light is collected at the grating side, which means that a compromise between side-mode rejection and output power has to be found. In that case, the required control is also a disadvantage.

Long-cavity laser diodes are realised by integrating an array of identical optical amplifiers with a wavelength selective multiplexer within one cavity. First demonstrations of this type of laser arrays used a multiplexer in a reflective configuration. The multi-channel grating cavity laser (MGC) (White *et al.* 1991) (Fig. 9a) is an extension of the external grating cavity laser. Stable, simultaneous operation at multiple wavelengths could be obtained and the issue of crosstalk in the common amplifier was mentioned for the first time. A solution in the form of a feedback scheme was proposed and demonstrated (Nyairo *et al.* 1992). However, the MGC laser is based on bulk components, which requires a very stable set-up. To overcome this, Kirby proposed a more compact version, based on the monolithic integration of an amplifier array and an etched diffraction grating (Kirkby 1990). Such a multiple array grating integrated cavity laser (MAGIC – Fig. 9b) was realised in 1992 (Soole *et al.* 1992a, b; Poguntke *et al.* 1993). This device had a low side-mode suppression and a high threshold current though. In 1993, the first device employing a phased-array demultiplexer was demonstrated (Zirngibl *et al.* 1994). However, this laser was not suitable for multi-wavelength operation.

Since 1994 several groups (Zirngible *et al.* 1994; Staring *et al.* 1996; Amersfoort *et al.* 1997; Doerr *et al.* 1999a, b; Joyner *et al.* 1999; Van Thourhout *et al.* 1998) demonstrated a multi-wavelength laser using a phased array in a transmissive configuration, as shown in Fig. 10. Most of these realisations made use of a monolithic integration technology. We developed an alternative technology based on the hybrid integration of an InP-amplifier array and a separate passive demultiplexer chip (Van Thourhout *et al.* 1999, 2000). The next paragraph describes the operating characteristics of long-cavity lasers in somewhat more detail.

3.2. OPERATING CHARACTERISTICS

Table 2 summarises some published characteristics of multi-wavelength laser diodes based on phased arrays (phased-array laser (PAL)).

3.2.1. *Number of channels*

The maximum number of channels for a PAL that was demonstrated is 18 (Zirngibl *et al.* 1996). In fact, this was a 24-channel device. However, one channel was defective and five had to be eliminated due to multi-passband

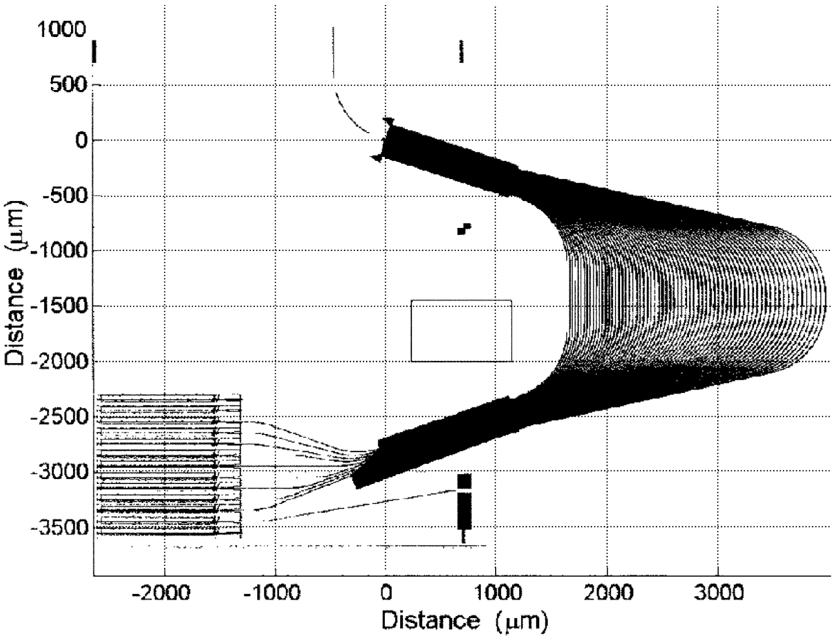


Fig. 10. Schematic of a PAL in a transmissive configuration.

lasing (the multiplexer was not chirped – see section on side-mode suppression). Simultaneous operation on all 18 channels was possible. However, a channel number between 8 and 10 is more frequently used. Since the device

Table 2. Published device characteristics of PAL diodes

	Joyner *et al.* (1999)	Doerr *et al.* (1999)	Doerr *et al.* (1997)	Staring *et al.* (1996)	Amersfoort *et al.* (1997)	Van Thourhout *et al.* (1999)	Van Thourhout *et al.* (1998)
N	9	10	8	9	8		
Channel spacing (GHz)	149.6	100	203	400	200	200	400
Accur. (GHz)	2	–	3	–	9.6		
λ_0 (nm)	1555	1600	1545	1545	1550	1530	1540
I_{th} (nm)	18–22	< 18	30	100–120	65–70	35	54
SMSR (dB)	> 55 (*)	> 55 (*)	54 (*)	20	40	40	35
P_{out} (mW)	1.0	0.58	0.6–1.5	0.1–0.4	0.65	3.5	–
I (mA)	100	100	190	200	90	100	
# Arms	68	70	80	50	–	–	–
Mux 3dB (GHz)	–	–	26	1.7 nm		60	120
L (GHz)	3.8	3.6	3.15	6 mm	7.5	10 mm	–
Common amplifier	No	No	Yes	No	Yes	No	Yes
Size (mm^2)	5.5 × 4.5	4.7 × 5.9	?	3.5 × 2.5	3 × 2	5 × 5	5 × 5
SOA length (μm)	950	900	2 × 950	500	400–600	400	400
Line width (MHz)	–	–	1	21	–	< 1	–

(* the phased-array is chirped, so the only visible side modes are these caused by wave mixing in the common amplifier under simultaneous operation).

yield decreases exponentially with the number of channels ($y_{\text{dev}} = y_{\text{chan}}^N$ with y_{chan} the yield per channel) this seems a good compromise between yield optimisation and device integration. The use of redundant amplifiers as demonstrated for DFB-laser arrays (Zah *et al.* 1997) is not possible here.

Very recently, a 40 (5×8) channel device with only 14 ($5 + 8 + 1$) amplifiers (100 GHz channel spacing) was demonstrated (Doerr *et al.* 1999a, b) which can be used as a rapidly and digitally tunable laser.

3.2.2. *Channel spacing*

The *channel spacing* of phased-array multi-wavelength lasers is determined by the passive demultiplexer and is, when correctly designed, very accurate. The minimum channel spacing demonstrated is 75 GHz (Doerr *et al.* 1995a, b). Designing a InP phased-array with smaller channel spacing (50 GHz) is more difficult and requires very stringent control on the process parameters since phase errors lead to a severe degradation of the crosstalk level (Dragone 1997).

The *channel spacing accuracy* is very good – typically an order of magnitude better than for short-cavity laser arrays – and determined by the FP-mode spacing. This reveals immediately a trade-off on the device length: decreasing the device length improves the single mode stability and the modulation bandwidth, but at the same time the FP-mode spacing is increased and thus the channel accuracy decreased (see Table 2 – (Amersfoort *et al.* 1997; Joyner *et al.* 1999)). The multiplexer is completely realised in passive material so neither degradation nor shift of the channel spacing accuracy has to be expected during the device lifetime.

3.2.3. *Absolute wavelength accuracy*

To obtain a good absolute wavelength accuracy, a stringent process control and characterisation is necessary. A deviation of the effective refractive index less then 0.1% already results in a 1 nm deviation of the central wavelength of the device. However, such accuracy is shown to be obtainable from chip to chip and wafer to wafer (Van Thourhout *et al.* 1998). The temperature may be used to tune the whole wavelength comb (which is also the case for short-cavity lasers). A typical tuning range of 0.11 nm/K is obtained. The wavelength is expected to be independent of drive conditions since the multiplexer is passive.

3.2.4. *Threshold current and output power*

For these integrated lasers to be useful, their power consumption per channel must be similar to that of their discrete counterparts. It is also true that the lower the threshold of a laser, the better its performance in the long term. The threshold current and the external quantum efficiency are predominantly determined by the cavity loss. The most important cavity losses are the multiplexer loss, which in turn is determined by the passive waveguide loss, and the active–passive transition loss, so an integration scheme minimising these is required. In Staring *et al.* (1996), the same p-doped cladding layer is used for both the amplifiers and the passive waveguides, resulting in an estimated waveguide loss of 20 dB/cm and high threshold currents (100–120 mA). However, intensive optimisation of the monolithic integration process led to devices (quantum well active layer) with a threshold current as low as 18 mA/channel and an output power between 0.8 and 1.2 mW at 100 mA (coupled to SMF) (Zirngibl *et al.* 1994).

Using a hybrid integration scheme as described in the previous paragraph, it is possible to optimise both the active and the passive part separately, resulting in a multiplexer loss lower than 2 dB. However, the active–passive transition loss is higher for hybrid integrated PICs compared to the monolithic ones. We have demonstrated devices (bulk active layer) with quite low threshold current (<35 mA), and to our knowledge the highest output power for a PAL reported until now: 3.5 mW for one channel operation and a total power of 6.2 mW when four channels are operated simultaneously.

3.2.5. *Side-mode suppression ratio/ASE noise suppression/longitudinal mode stability*

The SMSR is determined by both the suppression of the neighbouring longitudinal modes in the same passband as by the suppression of modes in another passband of the phased array. Multi-passband lasing (MPL) can be prevented by increasing the free spectral range (which increases also the size (Zirngibl *et al.* 1996)), by using bulk active material with reduced gain bandwidth (Amersfoort *et al.* 1997) or by chirping the phased array. The latter suppresses the phased-array neighbouring passband transmissivity by 5–10 dB thereby cancelling MPL completely (Doerr *et al.* 1996). Chirping the phased array has only influence on the mask design and does not alter the device fabrication. Moreover, it also allows to change the linewidth enhancement parameter α by moving the gain peak with respect to the central wavelength as is done for DFB lasers.

Obtaining single longitudinal mode stability and avoiding mode hopping is more difficult: for a typical 200 GHz PAL (3 dB bandwidth = 60 GHz, cavity length 10 mm), approximately 15 longitudinal modes fit within the passband. Fortunately, the modes are spaced closely enough in frequency so that their beatings cause a strong wavelength dependent gain compression as shown in Doerr *et al.* (1995a, b). This effect creates a stability region for the longitudinal modes around the filter peak. As long as the lasing mode stays within this region, single mode operation is obtained. However, when the lasing mode is moved with respect to the filter (when changing the current), it may exit the stability region and a mode hop will occur, the new mode ending up somewhere in the stability region. Mode hopping may be overcome in devices with two electrodes (Doerr *et al.* 1997).

3.2.6. *Modulation capabilities*

The long cavity limits the modulation speed of the PAL. We measured a bandwidth of 1.6 GHz for a 10 mm long hybrid integrated long-cavity laser (Van Thourhout *et al.* 2000). Direct modulation of a 16-channel device up to 622 Mbit/s (all channels modulated simultaneously) was demonstrated (Monnard *et al.* 1998a, b). When the PAL is used as a wavelength selectable source and no simultaneous operation of multiple channels is required, a modulator may be integrated on the same chip by attaching it to the output star coupler of the WGR, one period away from the shared amplifier connection (Fig. 11).

In Monnard *et al.* (1998a, b), a PAL is used as an eight-wavelength fast packet switching transmitter: a 2.5-Gbit/s stream is directed to eight different locations by sequentially turning on different channels of the laser. The switching time was less than 2.8 ns and limited by the electrical inductance of the packaging. If the amplifier is driven below threshold in the off state, the switching time increases to 10 ns.

3.2.7. *Laser linewidth*

Due to the long-cavity length, the linewidth of multi-wavelength PAL diodes is typically rather low. Several authors have reported values from below 1 MHz (see Table 2).

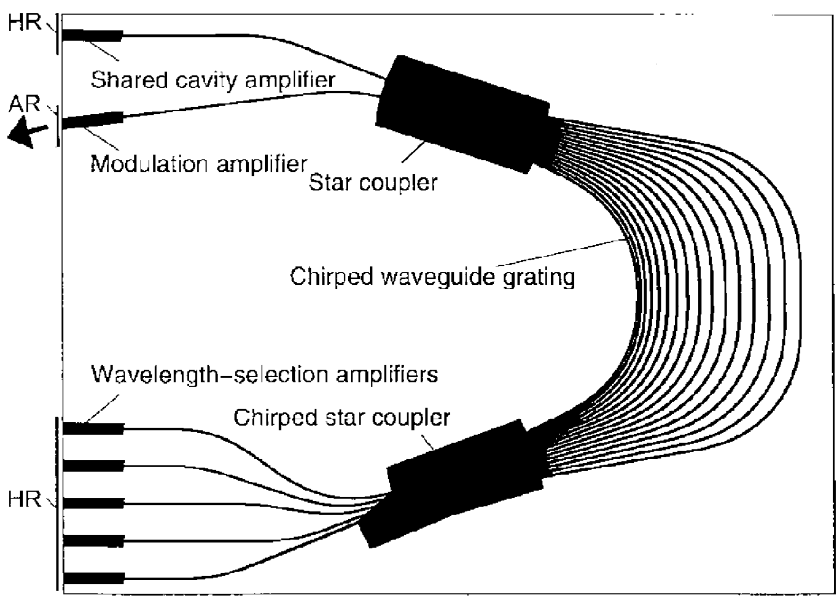


Fig. 11. PAL integrated with modulation amplifier.

3.2.8. *Control and reliability*

Since the wavelength spacing is fixed, control of only one wavelength channel is necessary to tune the whole wavelength comb to the desired wavelength. As already mentioned, the filter is realised completely in passive material so no degradation or shift is expected. When a common amplifier is used it may be necessary to use a feed-forward scheme when multiple channels are operated together to avoid crosstalk from carrier density changes (Doerr *et al.* 1995a, b). Another approach is to clamp the gain of the common amplifier (Van Thourhout *et al.* 1998).

Stringent reliability testing has not yet been published. However, since the typical device size is around 5×5 mm^2, which is quite big, there may be a problem for large-scale fabrication (Marz 1995).

4. Comparison of widely tunable and multi-wavelength lasers

Below, the main properties of multi-wavelength lasers and widely tunable lasers, indicating their potential advantages and disadvantages, are briefly described (Table 3). The properties listed for multi-wavelength lasers are mainly the typical properties of PALs (studied in AC332-APEX), whereas the properties listed for widely tunable lasers are those for the lasers studied in AC329-ACTUAL.

4.1. NUMBER OF CHANNELS AND CHANNEL SPACING

The channel spacing in (widely) tunable laser diodes can be made very small. It is rather the accuracy of the channel frequencies that is limited (e.g. due to

Table 3. Main properties of multi-wavelength and widely tunable laser diodes

	Multi-λ lasers (e.g. PAL)	Widely tunable lasers
Number of channels	16	Over 100
Channel spacing	75 GHz	12.5 GHz
Output power (in fibre)	1 mW	1 mW
Side mode rejection	40–60 dB	30–40 dB
Complexity of control	Simple, T-control	Complex control
Complexity of fabrication, packaging, characterisation	No grating, large area Leads to low yield	Higher yield, but characterisation involved
Modulation possibilities	622 Mbit/s	2.5 Gbit/s
Wavelength switching	4–10 ns	Depending on required accuracy, > 4–10 ns.
Need for extra components	No	Yes (e.g. combiner)
Cost and reliability	Multi-channel operation is potentially cost saving	A lot more expensive than multi-λ lasers

the limited accuracy of the control electronics and imperfections in the control in general). The number of channels depends on the channel spacing; since the total tuning range is typically several tens of nm it is the number of channels times the channel spacing that is limited. As a result, transmitter modules containing tunable lasers can be easily adapted if the channel spacing has to be reduced. Only the electronics controlling the laser have to be upgraded, but the laser does not have to be replaced.

The channel spacing in multi-wavelength lasers is typically limited by the design, whereas the number of channels is limited by yield considerations. The number of amplifiers/lasers on a single chip is proportional with the number of channels and a high number of amplifiers/lasers on a single chip obviously leads to a low yield.

4.2. OUTPUT POWER AND SIDE-MODE REJECTION

The output power in fibre is at the moment still unacceptably low for both the multi-wavelength and widely tunable laser diodes. Tunable laser diodes such as the three-section DBR or DFB laser possess a clear advantage in this respect. The three-section DFB laser e.g. can give about 5 dB more fibre-coupled output power over the entire tuning range than the four-section lasers and the multi-wavelength lasers (Hong *et al.* 1999). The SMSR on the other hand is sufficient for both tunable and multi-wavelength lasers.

4.3. COMPLEXITY OF CONTROL/EASE OF USE

Tunable laser diodes require complex control, including both control using electronically stored look-up tables and control based on feedback. Multi-wavelength lasers on the other hand just need temperature control and all channels can be adjusted to the channel plan grid by adjusting the temperature.

4.4. COMPLEXITY OF FABRICATION, PACKAGING AND CHARACTERISATION

Due to the large area of the chips in the case of multi-wavelength lasers, the fabrication yield will probably be significantly smaller than in the case of (widely) tunable lasers (Marz 1995). The fabrication itself is simpler for the specific case of PALs since there is no grating in these lasers as in widely tunable lasers. The advantage of a possibly higher fabrication yield is for the four-section widely tunable lasers undone by the fact that their characterisation requires significantly more time. Indeed, whereas widely tunable lasers typically require a characterisation time of 30 min (cf. 2.2), the characterisation of PALs is a question of minutes. The little tuning that is needed in such lasers can simply be done thermally. The characterisation time required for three-section tunable lasers is an order of magnitude smaller than for four-section tunable lasers and not much more than the time required for the characterisation of PALs.

4.5. COST AND RELIABILITY

The reliability of both (widely) tunable and multi-wavelength lasers is not well known and still under investigation. Concerning the cost, there is a clear advantage for the multi-wavelength lasers. This is because they can operate at multiple channels simultaneously, but also because their characterisation is much less time consuming than that of widely tunable laser diodes. The simultaneous operation at multiple channels implies that one package and optical pigtail, possibly including an isolator, can be shared by all wavelengths.

4.6. APPLICATION ADVANTAGES

The use of tunable lasers allows introducing entirely new network concepts. Conventionally, flexibility and reconfigurability in a WDM system are provided by optical cross-connects. However, when the number of channels increases, the routing and switching becomes a serious problem as the demands on and the complexity of the optical cross-connects increase steeply with the number of channels. With tunable lasers, (part of) the flexibility can be put at the transmitter end, allowing the use of static wavelength routers and/or simpler cross-connects.

5. Conclusion

In this paper, the performance of state-of-the-art widely tunable and multi-wavelength laser diodes has been described in some detail. The two types of lasers have then been put side by side to compare them on a few issues. From this comparison it can be concluded that there are advantages and disadvantages to both laser types. Multi-wavelength lasers have a clear cost advantage, whereas tunable lasers have a definite advantage in terms of channel spacing and number of channels. It could therefore be concluded that multi-wavelength lasers and PALs in particular are the preferred sources for WDM systems with relatively low channel count whereas widely tunable lasers will definitely be more attractive for WDM systems with high channel count and increased networking functionality and flexibility.

At present, the simpler three-section (DFB and DBR) tunable laser diodes possess the tremendous advantage of a much higher output power than both the multi-wavelength laser diodes and the widely tunable four-section laser diodes. However, significant progress in the output power of both widely tunable and multi-wavelength lasers should still be possible in the near future. The advantage of tunable lasers related to flexibility and new network concepts also has implications on output power requirements. Indeed, taking fully advantage of the flexibility of tunable lasers implies that channels are brought together in fibres using a combiner instead of a multiplexer. The use of a combiner obviously implies significant losses and therefore requires higher output powers from the transmitters.

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