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Polarisation behaviour of diode lasers with frequency selective feedback

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Abstract. The paper reviews recent results obtained with diode lasers used in external hybrid cavities with frequency selective feedback. Such cavities attract continuing interest for several reasons. They generate a tunable single laser mode with very low linewidths (usually a few tens of kilohertz). Very wide discrete tunable ranges over 100 nm for Fabry–Perot type and over 200 nm for quantum well lasers are achieved. They can be made to oscillate in a tunable mode having the desired polarization state, TE or TM and, in some cases, simultaneously at TE and TM. This is done by designing a cavity that increases strongly the TM/TE intensity ratio and by using coatings on one laser facet that greatly lower both TE and TM reflectivities. High-speed polarization switching in the gigahertz range is possible by inserting passive or active polarization selecting elements in the cavity. For all these reasons hybrid external cavities are attractive for applications in optical metrology, spectroscopy and optical communications. Moreover, the external cavity configuration allows the study of physical mechanisms in the laser diode by inducing on purpose phenomena that would have been otherwise impossible to achieve with free-running lasers.

Keywords. Diode lasers; external cavity, polarisation, tunability.

1. Introduction

External cavity semiconductor lasers with frequency selective feedback are well-established sources of tunable single-mode radiation. Their advantages lie primarily in their superior spectral performance relative to monolithic tunable diode lasers both in terms of broad-band tunability and narrow linewidth oscillation. Moreover, commerically available, low-cost Fabry–Perot laser diodes can be used. Their drawbacks are the inherent mechanical instability of the hybrid external cavity set-up and the low frequency modulation response speed. Despite these limitations, external cavity diode lasers (ECDL) continue to remain in the focus of scientific interest because of their proven applicability and their potential as single mode tunable sources in coherent lightwave communications, optical metrology and spectroscopy. Moreover, they offer the potential of added insight into the physical mechanisms of diode laser operation.

2. Wavelength tunability of ECD lasers with gratings

The basic configuration of ECDL with frequency selective feedback is shown in figure 1a (Murata & Mito 1990; Syvridis *et al* 1991). The mirror facet of the diode facing the grating has an antireflective (AR) coating. The light leaving this facet is collimated through a microscope objective and illuminates a diffraction grating which has the function of both a spectral filter with good spectral selectivity and a retroreflector to the laser. The external cavity length is usually much longer than the length of the diode laser (several centimetres vs. 200 to 300 mm). Assuming a coating with negligible rest reflectivity, one can consider the laser cavity as composed of the non-coated diode mirror and the grating. Only a small portion of that length (approximately a few per thousand) is filled with the active semiconductor material. An alternative set-up is to use an optical fibre to form the external cavity (figure 1b). A diffraction grating is either etched into or coupled to the fibre and acts as the wavelength selective element (Park *et al* 1986). The use of a bulk grating is, however, preferable to the fibre grating since it allows easy access to the cavity and is therefore more popular. The types of ECDL described operate in general in the so-called strong feedback regime where the power coupled back into the laser is an appreciable portion (about 20 to 40%) of the power leaving the coated facet. The radiation emitted from the uncoated facet is in general single mode with very narrow linewidth in the range of approximately 10 to 100 kHz.

The tuning of the wavelength is usually accomplished by rotating the grating around an axis parallel to the grooves (Murata & Mito 1990). This selects the feedback wavelength in the tangential plane of the rotation according to the Bragg condition. An alternative method is to translate the collimating objective parallel to the diode junction (Syvridis *et al* 1991). The broad-band tunability comes about because the tuning range of the central wavelength of the grating is larger than the gain bandwidth of the semiconductor material and consequently the whole gain bandwidth can be scanned, i.e. several tens to more than 100 nm for diode lasers depending on diode structure and on the spectral position of the gain maximum. The widest tuning ranges have been reported for Multi-Quantum-Well (MQW) lasers (Bagley *et al* 1990) because of their inherently wide gain bandwidths.

Each setting of the grating corresponds to a central frequency f of the radiation reflected back to the laser with a frequency bandwidth Df. Within this bandwidth there exist $Df/(c/2L)$ possible external cavity modes, c being the light velocity *in vacuo* and L the external cavity length. The frequency nearest to f which fulfils the gain and phase

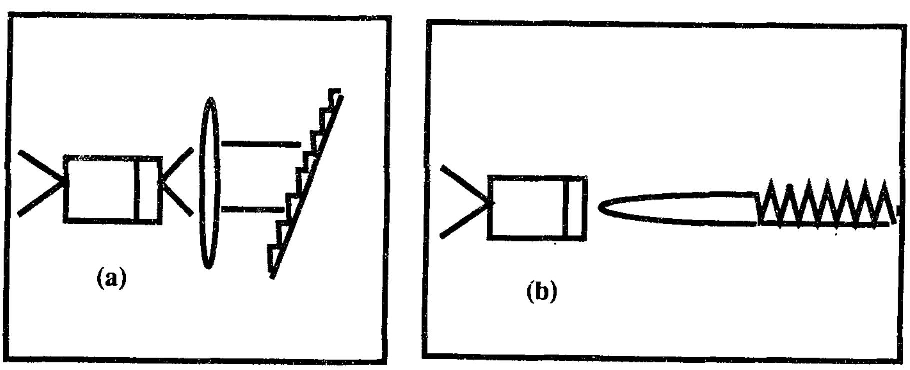

Figure 1. Basic configuration of an external cavity diode laser with frequency selective feedback: (**a**) external grating; (**b**) fibre grating.

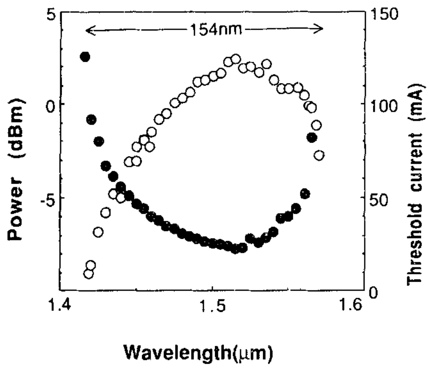

Figure 2. Optical output power and threshold current vs. wavelength of an ECDL using a grating. The laser was of Fabry–Perot type and had an integrated phase-control section. A tuning range of 154 nm was achieved (Notomi *et al* 1990).

conditions of the composite laser cavity will turn into oscillation. In principle, all external cavity Fabry–Perot modes under the gain curve of the diode laser can be scanned with the grating and come into oscillation provided the threshold condition is satisfied and the rest-reflectivity of the coating is negligible. A typical measured wavelength dependence of the optical power emitted from the uncoated facet and collected with a fibre is given in figure 2 (Notomi *et al* 1990). Single-mode oscillation is achieved here in the tuning range of 154 nm with a peak power of 2 mW reached at 1·52 μm which is also the wavelength at which the lowest threshold current is measured. A peak power of 550 mW has been obtained with an AlGaAs/GaAs QW ECDL with grating (Gavrilovic *et al* 1991).

The measured linewidths of ECDL lasers are typically below 100 kHz which is significantly narrower than those of free-running Fabry–Perot or even DFB lasers. It has been shown (Tkach & Chraplyvy 1986) both theoretically and experimentally that AR-coated lasers operating with external reflectors that produce a strong feedback – i.e. at least ten percent, as is the case for the set-ups discussed in this paper – operate in a stable regime, once the cavity has been carefully aligned and sufficient frequency selectivity is provided. This regime seems to be insensitive to phase variations of the light reinjected into the diode and also to other external optical perturbations that may cause line broadening and coherence collapse in weak feedback cases (Schunk & Petermann 1989). The switching time between selected wavelengths is, of course, long and cannot be expected to become less than some milliseconds due to the mechanical arrangement. Short switching times can be realised when tunable electro-optical or acousto-optical devices are used to implement the feedback mechanism (Murata & Mito 1990). A serious problem with ECD lasers using gratings is the medium and long-term mechanical instability. The use of precise piezoelectric controls of the translation and rotation stages and of vibration insensitive set-ups can somehow alleviate but not completely eliminate the problem. Good results can be achieved by using optoelectronic feedback mechanisms to control mode hopping (Ohtsu *et al* 1989) and to obtain stable frequency and power output.

The tuning with external grating cavities is, however, within a wide range which is not truly continuous. As the grating is rotated, the laser mode jumps between external cavity modes. The space between two consecutive modes cannot be tuned entirely. The reason is the phase mismatch between the reflected light from the grating and the light propagating in the laser diode. Moreover, the tuning through the internal modes is accompanied by a variation of the output power which is more or less periodic, the period being the internal mode spacing (Olsson & van der Ziel 1987). The term internal

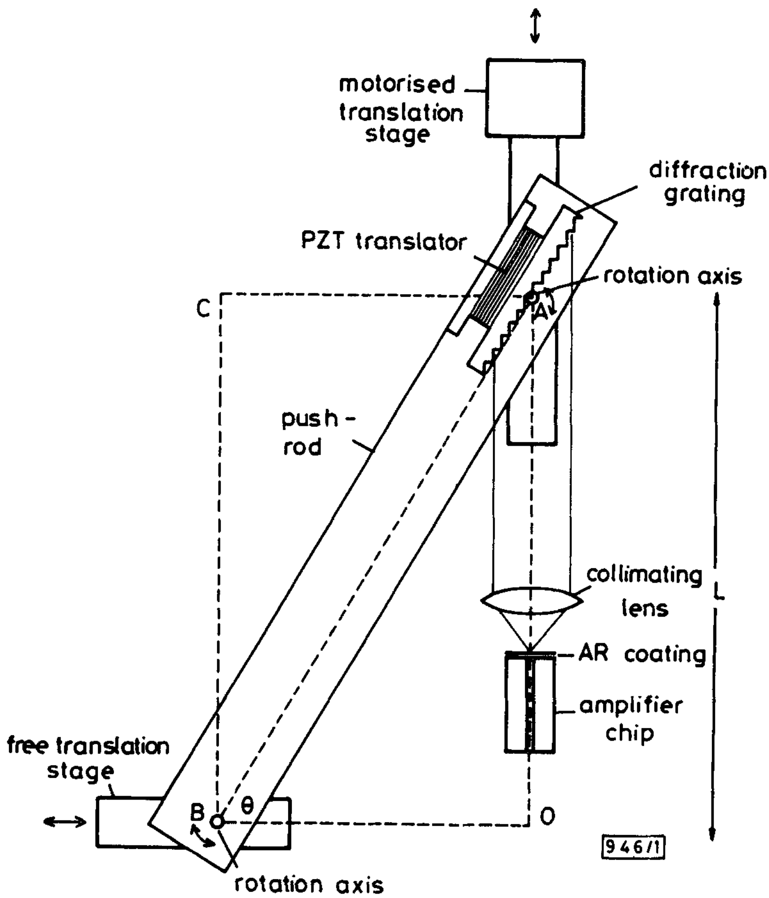

Figure 3. Set-up of a continuously tunable ECDL using a grating that can be rotated and translated so as to achieve continuous tuning without mode hopping (Favre *et al* 1986).

refers to the axial mode of the solitary diode laser without grating which develops because of the rest reflectivity of the coated facet. This variation can be minimised by the use of a very high-quality AR coating on the internal facet of the diode. True continuous single-mode tuning without mode hopping can be obtained when the diffracted wavelength imposed by the rotation of the grating coincides with a Fabry–Perot mode of the cavity. This is of course only so if the cavity length is changed simultaneously with the rotation of the grating. This method was first demonstrated by Favre *et al* (1986) and the set-up is given in figure 3. Impressive results – continuous tuning over 25 nm around 1·55 μm – have been reported recently (Nilsson & Goobar 1990). The mechanical adjustments needed must be performed with high accuracy since the frequency separation between two consequent resonant modes, which is inversely proportional to the cavity length, is very small. The output is single mode but the linewidth reduction may be less than optimum.

3. Polarization selectivity with ECD lasers

An FP diode laser can oscillate in either the TE or the TM mode but in practical diodes the emission is usually TE. This is because the TM mode has higher losses than the TE due to the lower facet reflectivity for TM and to usually a lower confinement factor (Agrawal & Dutta 1986). The external cavity is a practical means to induce the desired polarization to the laser, TE or TM, and to switch the radiation between the two polarization states.

In external cavities using mirrors as the feedback element, the insertion of a polarization controlling or shifting device into the cavity, like polariser or quarter-wave plate, has been shown to result in the emission of a TE or TM wave or even the simultaneous emission of both. When a polariser is inserted, its polarization angle relative to the *pn*-junction plane is used to change the optical losses of one state of polarization with respect to the other (Toda *et al* 1988). Quasi-single mode TE or TM laser radiation can be obtained when the loss differences are large whereas simultaneous multimode TE and TM radiation is emitted when the losses for the two states are approximately equal (Mitsuhashi 1982). In another arrangement, a combination of a fixed and a rotatable quarter-wave plate was used to induce simultaneous single mode TE and TM oscillation at different frequencies (Wakana *et al* 1987). The relative losses between TE and TM can be continuously varied by inserting an active element, like a KDP electrooptic intensity modulator in the cavity. Fujita *et al* (1987) demonstrated a two-arm, two-mirror cavity to produce polarization switching between two stable, single frequency TE and TM modes as the KDP was driven with a sawtooth voltage. By replacing one of the mirrors with a grating, polarization bistability was observed between two single modes TE and TM. This is caused by a hysteresis effect when the KDP modulating voltage is sweeping the oscillation back and forth between TE and TM. This phenomenon has been attributed to a nonlinear gain saturation effect of the laser. Polarization bistability can also be obtained if the KDP is replaced by a second diode laser in the cavity operated as a saturable absorber (Ozeki & Tang 1991) whereas the active laser is current modulated to produce switching and bistability.

An attractive feature of external cavities is the possibility of generating high-frequency TE and TM pulses with nearly 50% duty-cycle and 180° out of phase relative to each other. This polarization self-modulation can occur at frequencies above the relaxation oscillation frequency of the laser and does not need high-speed electronics (Loh *et al* 1990).

The polarization switching is performed by a passive element, like a quarter-wave plate inserted in the cavity or with a KDP crystal that is under DC bias to provide

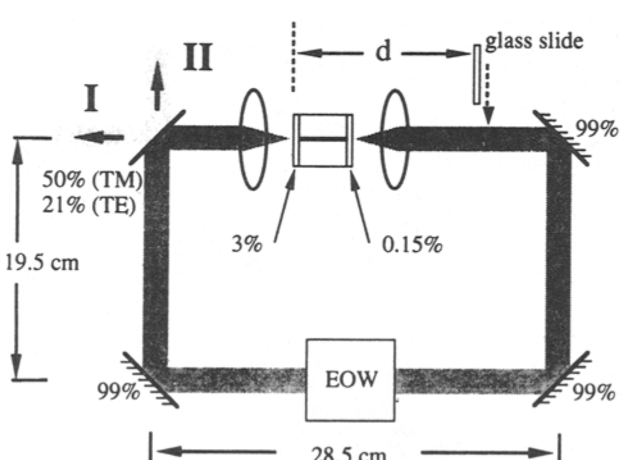

Figure 4. Ring external cavity set-up for multigigahertz polarization self-modulation. Frequencies above the relaxation oscillation frequency are possible (Loh *et al* 1990).

approximately the same threshold for TE and for TM radiation. Figure 4 shows the experimental set-up used to obtain multigigahertz polarization self-modulation (Loh *et al* 1990). With this set-up, frequencies close to 5 GHz were also obtained.

4. Combination of wavelength tunability and polarization selectivity

Until recently, frequency selective external cavities were used either as a means to tune the wavelength of a TE polarised single-mode laser or to select the polarization of the emitted radiation at a fixed wavelength. It is, however, possible to build ECDL that combine both features, i.e. generation of single-mode, widely tunable TE and TM radiation.

The polarization selectivity and wavelength tunability were obtained with a novel external cavity arrangement that allows easy mechanical adjustment and by minimising the TM losses in the external cavity configuration. The latter feature was achieved by selecting a laser structure with comparable confinement factors for TE and TM, applying an AR coating that minimises the overall reflectivity (less than 0·001 calculated, Besse *et al* 1991) and by using a diffraction grating that has higher efficiency for TM than for TE polarization.

The set-up that allows tunability of TE and TM radiation is shown in figure 5. It consists of three main blocks labeled A, B, and C. Block A is placed in a fixed position and contains the temperature stabilised laser diode placed on the edge of the heat sink in order to avoid light bouncing off the heat sink and affecting the performance of the system. Block B is mounted on an *XYZ* micropositioner and contains a tapered fibre to couple the light from the uncoated laser facet. Block C is placed on a piezoelectric *XYZ* micropositioner and contains a collimated AR-coated microscope objective in front of the AR-coated laser facet and a diffraction grating (Jobin–Yvon type 51016020) working at first order reflection. The reflectivity of the system objective-grating is 0·44 for TE and 0·65 for TM. The coupling efficiencies back into the laser are estimated to be around 24% for TE and 35% for TM.

A buried double-heterostructure InP/InGaAsP laser (Toshiba TOLD 350) with active region width 1·2 mm, thickness 0·1 mm and length 300 mm was AR coated on one facet with a double layer SiO/Al_2O_3. The thicknesses of the layers were calculated as in Besse *et al* (1991) and were optimised for each polarization as functions of the two-

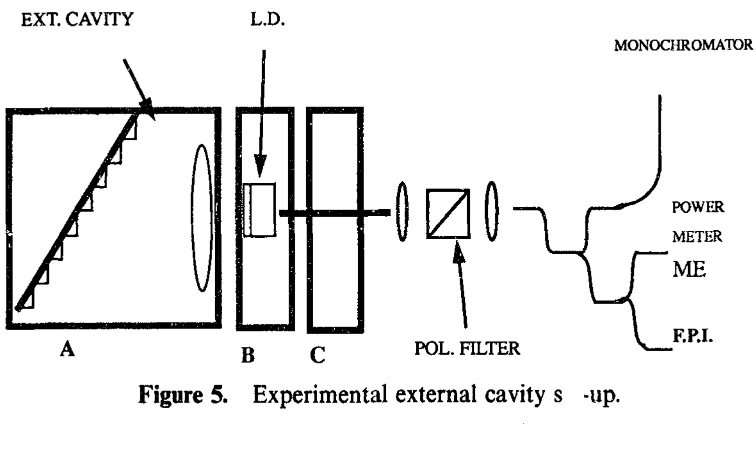

Figure 5. Experimental external cavity s -up.

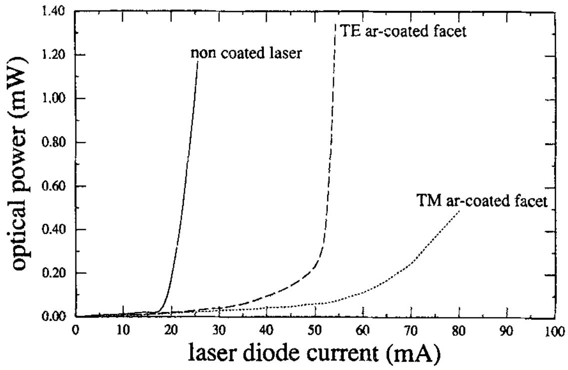

Figure 6. Optical CW laser power vs DC diode current before and after coating. Only TE emission was observed before coating.

dimensional laser profile. The deposition was performed in an *e*-beam evaporation chamber allowing real time *in situ* monitoring of the TE and TM radiation emitted from both facets. An experimental estimation of the reflectivity of the coating has been attempted using the coated diode as laser amplifer. By measuring the signal gain, spectral ripple and coupling efficiency in the input and the output of the amplifier a value of less than $0{\cdot}8 \times 10^{-4}$ has been obtained for the reflectivity at the wavelength of 1265 nm.

Figure 6 shows the optical CW power of the laser vs. DC diode current. Before coating, the laser emits mainly TE polarised radiation, the TM being negligible. The threshold is 20·5 mA at 19° C. After the coating deposition, the TE threshold is shifted to higher currents (52 mA) as expected because of the reduced facet reflectivity. What is now remarkable is that the coating allows lasing of the TM mode. The TM threshold appears at about 60 mA and for currents above the TM threshold both polarizations come into lasing. Both curves show a smooth transition from the non-lasing to the lasing state.

The spectra of the lasing TE and TM radiation of the coated solitary laser are shown in figure 7. The measurements were performed by placing a polariser in front of the free-running coated laser to isolate the TE from the TM radiation and spectrally resolving the radiation passing the polariser with a 0·5 m monochromator (resolution 0·04 nm). The DC current was 60 mA and the spectrum for the TE radiation had to be scaled down in order to allow a comparison with the TM radiation. A group of longitudinal modes appear separated by the internal diode mode spacing of approximately 0·7 nm. The TE and the TM modes are shifted with respect to each other because of the different net gain spectra (gain minus losses) for the two polarizations. The gain curves are shifted on the

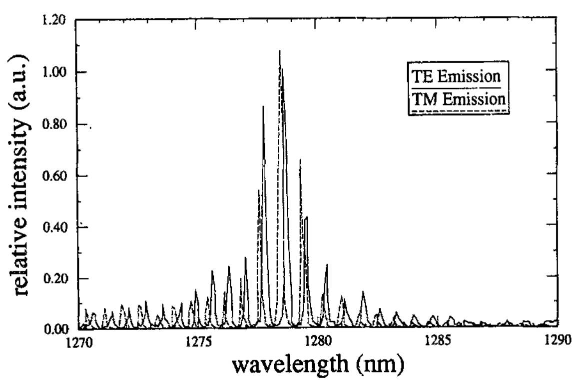

Figure 7. Radiation spectra of the free-running coated laser. Diode current 60 mA. The laser emits in both TE and TM simultaneously. The TE intensity is scaled down in order to permit comparison with the TM.

wavelength axis with respect to each other mainly because of the different wavelength behavior of the reflection coefficients of the coated facet for TE and for TM (Simon 1987; Besse *et al* 1991).

As is well known since early work with ECDL (Olsson & Tang 1981), a quasi-periodic modulation is imposed on the net gain curve of the laser vs. wavelength due to the rest-reflectivity of the coated facet when we place the laser in the external cavity. The spectral period of this modulation is the internal mode spacing of the laser diode. This applies to both gain curves for TE and for TM. The modulation depth for a given diode current density will depend on wavelength. The main reason for this are the spectral shapes of the reflection coefficients for TE and for TM of the coated facet which show in each case a minimum value at an optimum wavelength and increasing values as one moves away from the minimum. As a result, two gain curves are obtained, one for TE and another for TM, both of them showing the characteristic modulation. Due to the higher coupling efficiency of the cavity for TM than for TE, the net gain curve for TM will be shifted upwards to higher gains and its undulated shape will intercept the undulation of the TE gain curve (Syvridis *et al* 1992). As a result, we can expect a periodic alternation of spectral domains where the gain is higher for TE than for TM and vice versa, the period between two consecutive TE or TM peaks being equal to the internal diode mode spacing.

The wavelength tunability and polarization selectivity are achieved by translating the block C along the X axis parallel to the coated facet (figure 5). This is equivalent to a change in the angle of the grating relative to the direction of the collimated beam incident on it. By doing so, we can scan the wavelength axis and, by setting the diode current at a value higher than both TE and TM thresholds for the wavelength of interest, we expect to obtain an alternating succession of lasing TE and TM mode groups. Figure 8 demonstrates that this is indeed the experimental situation. It shows clearly that, as we scan through the wavelength axis, the emitted laser power alternates between TE and TM polarization. Once the cavity is tuned to a particular mode, it behaves stably for constant current and temperature. The DC diode current used was 60 mA and the power rejection ratio between the oscillating mode and the adjacent modes was measured to be always greater than 40 dB. Figure 9 shows the spectral characteristics as the cavity is tuned to successive power peaks. In the transition state between two consecutive polarizations, however, increased noise and, possibly chaotic phenomena, are noticed. This point needs further clarification.

The situation illustrated in figure 8 covers the low wavelength part of the spectrum. As one scans further towards longer wavelengths, the behaviour of the ECDL changes

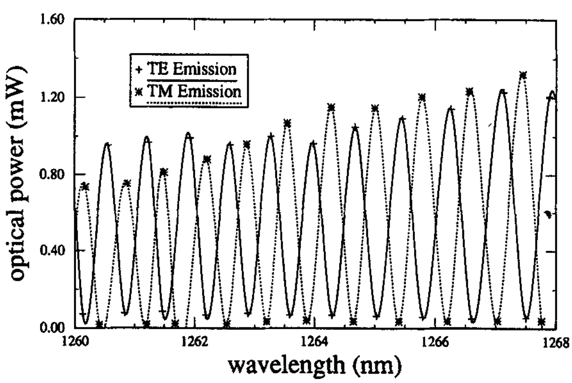

Figure 8. Power spectrum of the ECDL that emits in both TE and TM. Lower part of the spectrum . As the wavelength is tuned, the laser power alternates between TE and TM polarization. Diode current 60 mA.

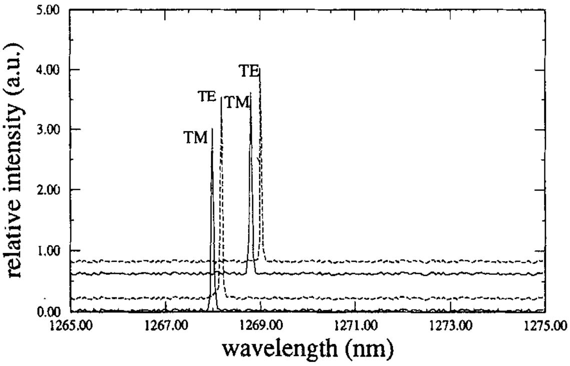

Figure 9. Spectral emission characteristics as the cavity is tuned to successive peaks of the emitted power. Tuning results in an alternation of the two polarization states. The spectra were measured with a polarisation filter.

gradually as shown in figure 10. The intensity of the TE polarized light decreases rapidly with increasing wavelength until a wavelength is reached where the laser no more emits the TE polarization but only emits the TM. The explanation of the behaviour shown in figure 10 follows the same line of reasoning as before. Above a certain wavelength, the modulated net gain curves for TE and TM do not intersect anymore, the TM gain lying higher than the TE gain. Consequently, the laser is tuned through the internal TM modes, the TE modes do not reach the oscillating threshold. The chaotic phenomena noticed before is particularly active as the TE polarization collapses into the non-oscillating state.

The threshold current vs. wavelength for the CW external cavity operation is given in figure 11. The discrete (coarse) tuning range for TM is 62 nm and for TE 26 nm. Continuous tuning without mode hopping could be observed around the wavelength of each oscillating TE or TM mode. Figure 11 demonstrates that above 1282 nm the threshold for the TE polarization increases so rapidly that the TE mode cannot oscillate any longer, as was shown in figure 10 (further current increase was not tried in order to avoid thermal damage of the laser). Below this wavelength and down to 1256 nm both polarizations oscillate whereas above this wavelength only TM lasing modes are obtained up to 1318 nm. The minimum threshold current for TE is 35 mA and occurs at

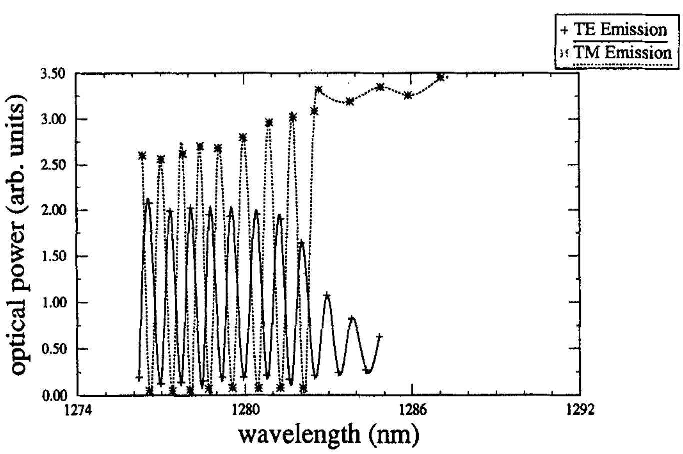

Figure 10. Middle part of the power spectrum of the ECDL. As the wavelength is increased, the TE polarization becomes weaker after oscillation ceases after about 1284 nm whereas tuning of the TM modes is obtained up to 1316 nm.

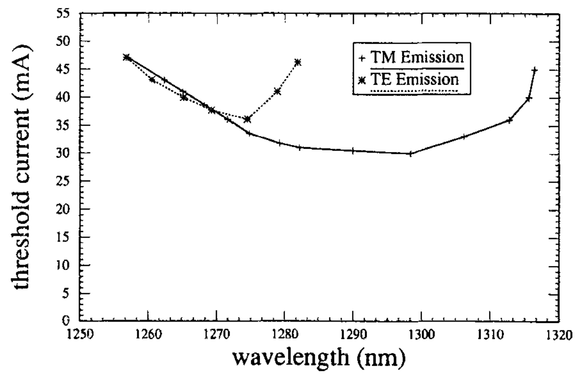

Figure 11. The threshold current vs wavelength for the CW external cavity operation and for the two polarisation modes.

1275 nm whereas the threshold current for TM is even lower (30 mA) because of the better coupling efficiency of the cavity for TM and is measured at 1298 nm.

5. Conclusions

External cavity diode lasers using hybrid set-ups with grating mirrors for the frequency selection are important in optoelectronics because of their attractive features. They emit a single laser mode whose wavelength can be tuned over a wide range, more than 100 nm for Fabry–Perot type lasers and more than 200 nm with quantum-well lasers. This is achieved by evaporating an antireflective coating onto one laser facet and using a high-quality external grating to select the desired wavelength. The linewidth is very small as compared to free running lasers and is usually a few tens of kilohertz. They can be made to emit the desired polarization, TE or TM, by placing a polarization selective element in the cavity. With such cavities, polarization bistability and switching at frequencies in the gigahertz region have been reported recently. It is, however, possible to obtain both wavelength tunability and polarization selectivity without additional elements in the cavity. A special cavity design and a diode with an antireflective coating that enhances the TM radiation as compared to TE have been employed to obtain discrete tunability for both polarizations. The results are explained by taking into account the modulation of the gain by the rest-reflectivity.

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