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Wavelength Control in Buried Heterostructure and Ridge Waveguide Lasers

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ABSTRACT

High density wavelength division multiplexed (HD-WDM) systems place stringent requirements on the absolute wavelength and wavelength spacing of the elements in Distributed Feedback (DFB) laser arrays. An analysis of the fabrication tolerances for ridge waveguide and buried heterostructure DFB lasers is performed, showing the fabrication-induced wavelength variations present in these types of devices.

Wavelength Division Multiplexing (WDM) is a powerful technique to access the tremendous bandwidth available in optical fibers by simultaneously transmitting two or more signals at different optical wavelengths over the same fiber [1]. The fabrication of multi-wavelength DFB laser arrays for WDM has been the focus of considerable attention [2.,3]. The absolute wavelength and wavelength spacing of the elements in the laser arrays is critical for system level performance. Systems requirements have specified wavelength control as tight as $\pm$ 0.2 nm for a given channel so that the wavelength of the transmitter signal and the passband of the demultiplexing element at the receiver end are properly aligned [2]. While temperature tuning can be used to move the wavelengths of all the elements in an array equally, temperature tuning can not easily be used to compensate for inaccurate wavelength spacing of the elements within an array. Consequently, the critical factors in the fabrication of WDM

DFB laser arrays are those which affect the device-to-device wavelength spacing. Since the final emission wavelength of a DFB laser is directly proportional to the modal index from the Bragg condition ($\lambda = 2 n_m A$, where n_m is the modal index and A is the DFB grating pitch), any variation in the modal index will have an effect on the emission wave] ength. An empirical formulation for the variation in the emission wavelength of a DFB laser can be written as [4]

$$\Delta\lambda = 2 \, A n_m A \approx (\partial\lambda/\partial w) \, dw + (\partial\lambda/\partial t) \, dt + (\partial\lambda/\partial P) \, dP + (\partial\lambda/\partial g) \, dg + (\partial\lambda/\partial B) \, dB + \Delta\lambda_a, \quad \text{Eqn. (1)}$$

where w is the ridge width; t is the layer thickness; *P is the* PL wavelength (material composition) of the layers; g is the modal gain at the emission wavelength; *B* is the DFB grating etch depth; and $\Delta\lambda_a$ relates to the mode spacing in an intrinsically dual mode DFB laser. These parameters will be the critical factors in determining the wavelength accuracy of elements in a DFB laser array.

Most of the published results on WDM laser arrays have focused on buried heterostructure (BH) DFB lasers rather than ridge waveguide (RW) devices. However, for absolute wavelength control the fabrication tolerances for BH lasers are more stringent than for RW lasers, due to the generally narrower active region and large index difference around the active region. An analysis of the fabrication tolerances for RW and BH devices is performed, showing the advantage offered by the ridge design. The wavelength control limitations that are common to both BI 1 and RW devices are discussed.

The lasers modeled in this paper are separate confinement heterostructure (SCI 1) t ypc designs, consisting of the following layers: $n+$ InP substrate, 100 nm InGaAsP ($\lambda = 1.2 \, \mu m$) SCI I layer, an active region of six 7.0 nm InGaAsP quantum wells separated by five 9.0 nm InGaAsP ($\lambda = 1,2 \, \mu m$) barriers, 100 nm InGaAsP ($\lambda = 1.2 \, \mu m$) SCH layer, 0.23 μm InP spacer layer, 80.0 nm InGaAsP ($\lambda = 1.18 \, pm$) etch stop layer, and 1.3 μm p-InP. The etch stop layer is required for the RW lasers to control the ridge depth and thus the An. The same layer structure was used in our BI I simulation for consistency. To mimic real devices as closely as possible, the following assumptions were made in our calculation: (1) the grating is etched into the top SCI I layer; (2) polyimide with a refractive index of 1.75 at 1.55 μm was used to planarize the RW device, and InP was used to bury the BH device; (3) the semiconductor indices of refraction were calculated from [5]; and (4) the typical active region (ridge)

widths of 1.0 μm and 3.0 μm are assumed for the BH and RW devices, respectively. The modeling was conducted using the effective index method. Although this calculation ignored the effects of propagation losses as well as the doping and carrier-indrrccrl index changes, a reasonable agreement was achieved with experimental results. These simulation results enable an understanding of the critical wavelength issues for a given WDM specification, and show the trends and relative magnitudes of the modal index changes produced by various perturbations in the device design, fabrication and growth.

Results: The first term in equation (1), the width variation, dominates the variation of the modal index [4]. Fig. 1 shows the modal index variation for both BH and RW lasers as a function of the active layer (ridge) width - it is the slope of these curves that gives the sensitivity of the laser emission wavelength to the width. For a variation of ± 0.1 μm in the width (produced by lithographic and etch limitations), the BH laser emission will be ± 1.3 nm, and the RW laser will be ± 0.1 run (Table I shows the relative size of all the discussed effects). This result reveals an important problem with employing BH lasers as WDM transmitters in an array, and demonstrates the advantage that RW lasers have for WDM array applications. The large Δn in BH lasers requires a narrower mesa to keep BH lasers single mode, which means that a given size variation in the BH width will have a larger percentage change in the BH width and thus have a larger effect on the modal index than the same variation will have in a RW laser, Furthermore, the larger An in BH lasers gives the B II laser a larger slope at *all* widths in Fig. 1.

The other growth and fabrication related effects represented in Eqn. (1) are similar for RW and BH devices, and contribute effects that arc much smaller. Growth non-uniformities across a wafer and from wafer-to-wafer - leading to thickness and composition variations - also cause a change in the modal index of a laser. The effect of layer thickness variation on the modal index was calculated versus the percentage change in the layer thicknesses, from - 10% to +109. (all the layer thicknesses in the structure were changed). The results for both BH and RW lasers were linear over this thickness variation. For a 3 μm RW and a 1 μm BH, the modal index changes by 7.7 x 10^{-4} and 5.7 x 10^{-4} for each 1% change in the layer thicknesses, respectively. The wavelength change at 1.55 μm would be (using $\Delta\lambda = 2 \Delta n_m A$, and

Λ=240.0 nm) --0.37 run for a RW laser, and - 0.28 nm for a B I I laser. Compositional changes to the quaternary guiding layers will also produce changes in the modal index. The composition of the λ = 1.2 μm InGaAsP SCH layers were varied from λ = 1.19 μm to λ = 1.21 μm in our model, and the effect on the final modal index determined. Over this range, the modal index variation is linear with composition change. The modal index of a 3.0 μm RW laser changes 1.7 x 10^{-4} per nanometer wavelength change in composition, and for a 1.0 pm BH laser the change is 1.3 x 10^{-4} per nanometer. Compositional changes to the active layers, which arc very thin, have only a small effect directly on the modal index. However, compositional variations in the active layers can lead to gain variations, which cause (through the Kramers-Kronig relations) modal index variations [6]. The variation in the modal index with threshold gain variations can be expressed as [7]

$$\Delta\lambda = \lambda^2 \, \alpha \, \Delta g_{th} \, / \, 4 \, \pi \, n_m \qquad \qquad \text{Eqn. (2)}$$

where g_{th} is the threshold gain, and a is the linewidth enhancement factor. As an estimate of the size of this effect, using α = 2 and Δg_{th} = 20/cm, $\Delta\lambda$ -0.24 nm for both BH and RW lasers.

The control of the DFB grating depth is typically of the order oft 10.0 nm. his variation in the etch depth leads to a variation in the modal index. The modal index of a 3.0 μm RW laser changes 6.1 x 10^{5} per nanometer change in etch depth, and for a 1.0 μm BI I laser the change is 4.7 x 10"' per nanometer. Alternative designs with less sensitivity to the grating depth alleviate the dependence of the emission wavelength on the grating etch depth accuracy [8].

The other large term in Eqn. (1) is $\Delta\lambda_{sb}$. This term originates from the intrinsic dual mode nature of DFB [9], where the mode On either side of the stop band can last. The stop band width can be calculated from the approximate expression found in [10]

$$\kappa L = \pi/2 \, (\Delta\lambda_{sb}/ \Delta\lambda_{F} \, , - \, \Delta\lambda_{F-P}/ \Delta\lambda_{sb} \,) \qquad \qquad \text{Eqn.}$$

(3)

where κL is the grating coupling coefficient and $\Delta\lambda_{F-P}$ is the Fabry-Perot mode spacing. For a device with a κL of 1-2 and a cavity length of 300 pm, the $\Delta\lambda_{sb}$ is 1-2 nm. Since the emission wavelength of

the DFB laser must be controlled to ~O.? nm to tit in pre-assigned channel allocations in a WDM system, this uncertainty in the emission wavelength is not tolerable. A method must be used to deterministically set the Bragg mode that lases. A significant amount of research has successfully pursued the use of either phase-shifted [3] or complex-coupled devices [11] to precise] y set the lining mode. Both types of devices remove the dual mode degeneracy found in standard DFBs and have only a single DFB mode to lase in.

Conclusions: Many factors affect the modal index, and thus the emission wavelength, of semiconductor liners. Both RW and BH lasers are affected by a number of processing and growth related variations. Phase-shifted or complex-coupled gratings can be used to avoid the wavelength uncertainty found in dual mode DFB lasers; and a separate grating layer (away from the active region) can solve the grating etch difficulty. The other processing and growth related parameters arc unavoidable; however, through careful optimization-of device fabrication, the effect of these other parameters can be minimized. While the variations discussed can cause significant wavelength shifts across a wafer and from wafer-to-wafer, over the small area occupied by a single array the variations should be smaller, allowing for a reasonable yield. Table I shows that all the effects can cause wavelength variations > 0.2 nm. However, over the small wafer area occupied by a single array, the device-to-device variation should be small; from one array to another, it may be significant, requiring temperature tuning to bring one laser array output into alignment with another. As the width variation in the waveguides is seen to be the largest source of variation in the emission wavelength, the reduced dependence on the width found in ridge waveguide devices makes a strong case for their use in WI)M DFB laser arrays.

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Table I Effect of process variations on the final emission wavelength of 1.0 μm BI I and 3.0 pm RW lasers, using $\Delta\lambda = 2$ An$_m$ A and A = 240.0 nm.

Effect	Typical variation	Modal index effect (x 10^{-4})		wavelength effect (rim)	
		BH	RW	BH	RW
dW	± 0.1 μm	27.6	1.6	1.3	0.1
dt	± 1%	5.7	7.7	0.27	0.37
dP	± 5 nm	6.5	8.5	0.31	0.41
dg	± 20/cm			0.24	0.24
dB	±10 nm	4.7	6.1	0.23	0.29
Δλ				1-2	1-2

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