Use of Inverse-Fourier Design Method for Index-Patterned Laser Design

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***Abstract*— We investigate the impact of different real space slot distribution functions on threshold gain selectivity in index-patterned lasers, showing how careful choice of function should ensure high yield of devices which emit at or near a target wavelength.**

***Keywords*— Discrete-Mode Fabry-Perot, Inverse Scattering Design, Transfer Matrix Method**

I. Introduction

The use of index-patterned Fabry-Pérot lasers, where a small number of slot-like features are introduced along the laser cavity, is well established as a route to low cost, reliable single-frequency devices [1]. We use a Fourier-transform based inverse scattering method here to show how a modified choice of inverse function can deliver a significant improvement in modal threshold gain selectivity compared to the originally proposed use of a constant inverse function for slot selection [2]. We propose that the approach used can deliver a high yield of devices, with emission wavelength at or close to a target wavelength.

II. Mode Selection Function

The inverse-scattering process involves taking a desired mode-selection envelope at threshold and performing an inverse-Fourier cosine transform, which is then weighted to give the target function. Previous work has identified the sinc function $\left(\frac{\sin(k-k_0)L}{(k-k_0)L}\right)$ as an ideal mode selection function, which can select mode m_0 with wavenumber k_0 (sinc(0) = 1) while in principle leaving all other modes unperturbed ($\mathrm{sinc}(n\pi) = 0$ for integer $n \neq 0$). The inverse Fourier transform of sinc from wavenumber into cavity space gives the constant real-space function $f(\epsilon L) = 1$, where the cavity of length L is defined to lie in the region $-\frac{1}{2} \leq \epsilon \leq \frac{1}{2}$. The difficulty with this target real-space function is that it requires a significant number of the perturbations introduced to lie close to the center of the laser cavity (near $\epsilon = 0$). This arises because the perturbation introduced by an ideal slot should introduce a quarter-wavelength sub-cavity which is an integer number of half-wavelengths from the more distant mirror, and therefore an odd number of quarter wavelengths from the closer mirror. Light scattered to the farther mirror then adds to the modal gain, while light scattered to the closer mirror reduces the overall modal gain. Consequently, the impact, $\Delta\gamma$, of a slot at position ε on mode selection scales as

$$\Delta\gamma(\varepsilon) \propto |r_l| e^{\varepsilon\alpha L} — |r_r| e^{-\varepsilon\alpha L}, \qquad (1)$$

where $\alpha = {}^{1}\!/_{L} \ln\left(\frac{1}{|r_l r_r|}\right)$, and r_l and r_r are the mirror reflectivities. This creates a difficulty in the design. Features introduced near the facets have a much greater impact than features introduced in the center of the cavity. This motivates us to choose functions with a more even distribution of slots along the cavity after being weighted by the cavity function. Fig. 1 shows how functions with greater weight towards the cavity mirrors should have improved gain selectivity compared to the cavity function $f(\epsilon L) = 1$.

There is in addition no guarantee to form a half wavelength cavity to the farther facet when fabricating a slotted laser. For an ideal cavity, the mode selection spectrum is given by the cosine transform of the weighted design function. However, as the phase changes with respect to the facet, the mode selection function is determined as a linear combination of the cosine and the sine transform of the weighted function, with the sine contribution to the mode selectivity function for mode $m_0 + \Delta m$ given by [2]:

$$G(m_0 + \Delta m) = (—1)^{\Delta m} \int_0^{1/2} f(\varepsilon) \sin(2\pi\varepsilon\Delta m)\, d\varepsilon. \qquad (2)$$

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III. RESULTS

As a confirmation of this 1st order perturbation design approach, we used a transfer matrix method (TMM) [3] to investigate the effects of higher order scattering omitted in the 1st order design model. As the TMM method becomes unstable at gain levels at or just above threshold, we estimate how threshold gain varies with mode number in the TMM case by calculating the gain required for each mode to reach a fixed high output power, close to but just below threshold. The TMM results confirm that 1st order inverse scattering approach provides an excellent estimate of mode selectivity for each inverse function used. Implementation of the $f(\epsilon L)$ = 1 function (red curves, Figs. 1(a) and (b)) requires many slots near the center of the cavity, reducing the overall gain selectivity that can be achieved. The Fourier transform of the inverse function $f(\epsilon L)$ = $|\epsilon|$ partially selects the two modes neighboring the primary mode (green curves), but gives greater overall mode selectivity, due to a higher proportion of slots being near the laser facet. Investigating more complex inverse scattering functions, we find that $f(\varepsilon L) = \varepsilon sin(2\pi\varepsilon)$ leads to a further improvement in selectivity for the selected mode (blue curves).

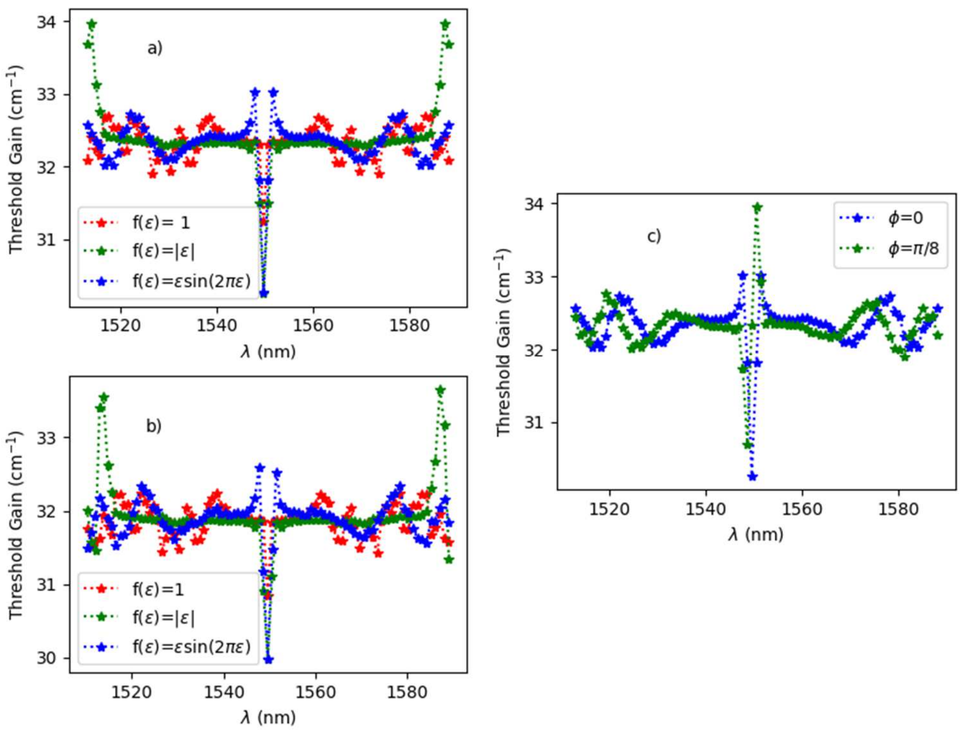

Fig. 1. Threshold gain dependence on mode number for inverse functions $f(\epsilon L)$ = 1 (red), $f(\epsilon L)$ = $|\epsilon|$ (green), and $f(\varepsilon L) = \varepsilon sin(2\pi\varepsilon)$(blue), calculated (a) using 1st order scattering model and (b) using TMM approach, assuming 20 ideally placed slots in each case. (c) Calculated threshold gain dependence on mode number for $f(\varepsilon L) = \varepsilon sin(2\pi\varepsilon)$, assuming ideal slot positions (blue, $\phi = 0$), and slots shifted by 1/8 of a wavelength with respect to facet (green, $\phi = \pi/8$).

Given the uncertainty in slot position relative to the facet when fabricating a slotted laser, it is important to know how the mode selection function changes as the slots are moved with respect to the farther facet. Fig. 1(c) shows the calculated threshold gain dependence on mode number for $f(\varepsilon L) = \varepsilon sin(2\pi\varepsilon)$, comparing an ideal slot distribution to one where each slot is shifted by one eighth of a target wavelength, λ_0, as determined based on (2). The phase shift here leads to a strong threshold gain reduction for the neighboring mode – hence an error in phase can still allow strong mode selection close to the target wavelength. We calculated the threshold selectivity for the three chosen design functions, as each were cycled through one facet phase error cycle of $\lambda_0/2$, confirming that the function $f(\varepsilon L) = \varepsilon sin(2\pi\varepsilon)$ should deliver a higher yield of devices which emit at or near the target wavelength.

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