Thermo-tuning and energy redistribution in microcavity solid-state dye lasers

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Abstract:
Wavelength tunability of a microcavity solid-state dye laser is modeled by the finite element method (FEM). We investigate the combination of thermoelastic expansion and thermo-optic effects to tune the microcavity resonant wavelength. An optimized size of the laser microcavity is defined depending on the operation wavelength bandwidth and the glass temperature of the gain material. We also report a new effect of mode depletion specific to our microcavity and excitation scheme.

1. Introduction
Lasers have become enabling components in the rapidly progressing nano-sciences and bio-applications based on photonics [1,2]. Several tasks in sensing and monitoring techniques, such as drug screening, massive testing of biological specimens, and implementation of “lab-on-a-chip” systems, require tunable lasers in the visible range [2,3]. In comparison with semiconductor lasers or LEDs, dye lasers offer favorable features: high brightness and coherence, narrow line width of radiation, and broadband tunability [4]. On another hand, whereas the most advanced results with tunable micro-scaled lasers were demonstrated for devices of sizes of several tens of micrometers [5,6], nano-imprinting lithography [7] allows to manufacture such components with feature size about 10 nm easily and inexpensively. Moreover, recent improvements of dye properties, such as stability against photo-bleaching and aggregating at high concentrations, greatly increase the attractiveness of solid-state dye lasers for micro- and nano-photonics applications [8,9]. In this paper, using FEM in Comsol Multiphysics, we consider wavelength tuning in a microcavity for solid-state dye laser; we investigate the optimal size of the microcavity depending on system requirements; finally, we also observe significant depletion of the odd longitudinal modes and enhancement of the even laser modes. This effect can enhance the device tunability since it broadens its free spectral range (FSR), which prevents mode hopping. Additionally, it allows minimizing the number of mode selective components to provide single-mode operation.

2. Method: wavelength tuning by thermoelastic expansion and thermally induced refractive-index change
We consider a solid-state microcavity laser with a design similar to that of the liquid dye laser reported recently [10]. Despite the successful demonstration of laser operation, microfluidic dye lasers may exhibit problems related to further downsizing due to the change of specific liquid properties such as viscosity, surface tension, and thermo-mechanical coefficients. A solid-state variant provides more versatility. To keep the model simple yet realistic, we restrict the analysis to a planar (2D) geometry with TE waves. The randomly distributed dye molecules emit spherical waves propagating along the cavity plane and simulate multi-point excitation (MPE) source. Typical values of the refractive indices are: \( n_{\text{dye}} = 1.43 \) in the Rhodamine 6G (Rh6G) + Polymethyl methacrylate (PMMA) gain section and \( n_{\text{pol}} = 1.6 \) in the SU-8 microcavity. We also include dispersion and losses but not amplification since we are only interested in the structure of the mode patterns. One property of the cavity is that all modes propagate with the same effective optical path \( L_{\text{eff}} \) [10].
\[ L_{\text{eff}} = 2(n_{d-p} l_{d-p} + n_{\text{pol}} l_{\text{pol}}) \], (1)

where \( l_{d-p} = 4 \mu m \) and \( l_{d-p} = 0.2 \ l_{\text{pol}} \) are as featured in Fig. 1. The radiation is out-coupled by tapping the evanescent field at an air gap \( l_{\text{air}} = 0.03 \ l_{\text{pol}} \) on the boundary \( \Gamma \) of a prism outside the cavity. We tune the output wavelength by heating the cavity thereby inducing two effects counteracting each other. To warm-up the structure, we use Joule effect by making a current circulate in metal rods (wires) placed such as the disturbances to the electric field and cavity distortions are minimized (Fig. 1). The reversible thermoelastic expansion will increase \( L_{\text{eff}} \) whereas the refractive indexes drop since the thermo-optic coefficients are negative:

\[
\frac{dn_{\text{pol}}}{dT} = \frac{dn_{\text{d-p}}}{dT} = -2.92 \cdot 10^{-4} K^{-1}[4,11].
\]

We design the system to make the latter effect predominant. Moreover:

\[
\Delta L_{\text{eff}} = \left( 2.4 \frac{dn_{\text{pol}}}{dT} + 1.7 \alpha_{\text{pol}} \right) l_{\text{pol}} \Delta T , \quad (2)
\]

where \( \alpha_{\text{pol}} = 50 \cdot 10^{-6} \) is the coefficient of thermal expansion (CTE) of SU-8 [11]. The expansion of the microcavity corresponding to a heating of 100 K and corresponding wavelength shift is illustrated in Fig. 2.

Figure 1. Layout of the microcavity. Figure 2. Blue shift with heating of 50 K and 100 K.

3. Results: wavelength tunability and microcavity size optimization

The microcavity mode spectrum includes several resonant wavelengths that satisfy the phase matching conditions for a cavity round trip. Resonant wavelength \( \lambda_m \) and mode number \( m \) are linked by:

\[
\lambda_m = \frac{L_{\text{eff}}}{m - \varphi/2\pi} , \quad (3)
\]

where \( \varphi \) is the phase change caused by the reflections at the microcavity walls. We operate around the peak of emission of Rh6G, i.e., 530 nm, corresponding to \( m = 28 \). Since the thermo-optic effect is predominant, we obtain a blue shift of 8nm for a temperature increase of 100 K. \( l_{\text{pol-opt}} \Delta T = 963 \mu m K \) relates the optimal base length of the cavity \( l_{\text{pol-opt}} \) fulfilling the condition: tunability=FSR. This allows choosing the best trade-off in function one’s needs. If a wide tunability is key parameter then a bigger cavity should be chosen since the glass temperature \( T_g \) of the materials limits their range of operation. PMMA and cross-linked SU-8 have respective \( T_g \) of 372 and 473 K. On the other hand, if one’s interest lies more in high integration density with low temperature increase to enhance the dye’s lifespan then a smaller cavity will be designed.
4. Odd mode depletion and enhanced efficiency of even resonance modes

Studying thermally induced tunability of the microcavity dye laser with MPE source, we also obtained depletion of odd longitudinal modes, whereas the even modes were strongly enhanced (Fig. 3). This differs from modeling the microfluidic dye laser with single-point excitation (SPE) [10]. Fig. 3 displays the electric field power integrated along the out-coupling boundary $\Gamma$ (Fig. 1). For a proper comparison, the total excitation power in both configurations is equal. We can explain the phenomenon using the concept of cavity modes which require satisfying the phase-matching conditions for wave round trips along the closed optical path. The microcavity with the gain section placed in the central part possesses spatial symmetry about the horizontal axis passing through the central slab. The position of the excitation source relative to this axis and the mode parity (treated as the parity of the mode number) play an important role on how efficiently the pump energy is coupled into the cavity modes. To clarify this relationship, we consider the mode spectra for two different positions of the SPE sources placed far from and close to the horizontal symmetry axis, i.e., points A and B in Fig. 5 respectively. The corresponding mode spectra are illustrated in Fig. 4. We can reasonably explain this phenomenon with different coupling efficiencies of the SPE pumping wave into the cavity modes with odd and even numbers using the mutual symmetry between the cavity modes and the location of the excitation source.

When the point source (acting as 2D spherical wave) is placed close to the cavity edge, point A in Fig. 5, the phase fronts of the spherical wave (solid line) cross the mode path (dashed line) at points which in all likelihood have different phases for each mode, for example, pairs 1-2 and 3-4. Although, by symmetry, the even numbered modes would have the same phase at point pairs 1-1' and 3-3', the phase of the excitation wave would not match. In such a case, no favorable conditions are created for the coupling of the pump excitation into the modes with different parities (Fig. 4, red line). Next, we consider the excitation source at the center of the cavity, point B in Fig. 5. For the even numbered resonance modes, the symmetrical cavity geometry leads to the same phase of the optical wave (dashed line) at every pair of points placed symmetrically at equal distances above and below the horizontal axis, e.g., point pairs 1-2 and 3-4. Since the SPE source emits a spherical wave (solid line), such a circumstance ensures an efficient transfer of the excitation energy into the cavity mode at these points due to constructive superposition. For the same working conditions, the odd numbered modes do not provide similar phase matching between the cavity modes and the spherical excitation waves, since the phases of the mode wave at point pairs 1-2 and 3-4 are no longer equal. Thus, the efficiency of the excitation coupling into the odd numbered modes is weaker (Fig. 4, blue curve). Using the excitation with multiple point sources randomly placed in the central part of the cavity amplifies the effect.
5. Conclusion
In this paper, we have considered thermal expansion and thermo-optical effects in a laser microcavity to obtain wavelength tunability. Their total contribution results in a 8 nm blue shift of the resonance mode wavelength under heating of the microresonator with 100 K above the room temperature. The cavity design, with the gain material simulated by MPE placed in the central polymer bar demonstrates the depletion of odd modes and enhancement of even lasing modes. The effect allows tailoring the tunability of microcavity lasers since it increases the free spectral range while keeping the cavity size small enough. We attribute this effect to the symmetry relation between the cavity shape and allocation of the excitation sources.

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