Chapter 1

INTRODUCTION

In this thesis I am going to introduce two categories of lasers: sub-micrometer-scale cavity semiconductor lasers, and millimeter-scale polymer-based dye lasers. In the first category, I will talk about two kinds of ultra-small cavity designs. The first is the submicron microdisk cavity and the second is the photonic crystal defect cavity. In the second category, I am going to talk about: the microfluidic one-dimensional DFB dye laser, and the solid-state two-dimensional circular grating DFB dye laser, with a focus on the potiential application on the micro optofluidic “lab-on-a-chip”. In the end, I will talk about how we can apply these lasers to the build a lab-on-a-chip by developing a technique for the molecular dynamic study in the solution.

1.1 Background and motivation

As does all matter exhibiting the wave-particle duality, light or electromagnetic radiation simultaneously exhibits properties of both waves and particles. In the scope of our research, both properties are substantial. The elementary particle that defines the light is the photon. There are many means of photon generation (many sources of light). In the semiconductor material we are working on, photons are produced through the energy transferred by either external photon pumping or the recombination of electron-hole pairs. In the dye materials, the photons are generated by external photon pumping only. Of the three macroscopic properties of light (photons)—intensity, frequency, and polarization—we will mainly focus on the property of frequency, and we will mainly work on how to control the light within a small space, and together with gain material, how to form a laser, a “single-frequency” light source. In physics, a laser is a device that emits light through a specific mechanism for which the term “laser” is an acronym: Light Amplification by Stimulated Emission of Radiation. In contrast to a light source such as the incandescent light bulb, which emits in almost all directions and over a wide spectrum of wavelength, laser emits light with a well-defined wavelength (or color, normally in levels from submicron to tens of microns) and normally in a narrow and well-defined beam. These properties can be summarized in the term “coherence”, and these properties have made lasers a multi-billion dollar industry. The most widespread use of lasers is in optical storage devices such as compact disc and DVD players, bar-code readers, and laser pointers. In industry, lasers are used for cutting steel and other metals, and for inscribing patterns (such as the letters on computer keyboards). Lasers are also commonly used in various fields in science (especially spectroscopy), typically because of their well-defined wavelength or short pulse duration (in the case of pulsed lasers). Most importantly, lasers are also used in optical integrated circuits for optical telecommunication, as well as in biological, chemical, and medical applications.

For the first category of laser, we are trying to explore the limit of the miniaturization of laser cavities and to develop nanophotonic lasers (microdisk and photonic crystal lasers) for applications including use in chip scale optical networks, ultra-small optical spectroscopy, and biological and chemical sensors. The nanolasers will be efficient and compact multi-wavelength light sources with greater density and modulation speed (over 100 Gb/s) than vertical cavity surface emitting lasers. Fast detectors for light have already been developed in well-established silicon CMOS processes for sensitive receivers, and these lasers can provide optical solutions to the interconnect problems for the next generation of high-speed processors and aerospace platforms. Moreover, it will be possible to assemble these devices into complex systems that permit signal processing and optical logic functions before signal conversion from the optical into the electrical domain.

For the second category of lasers, we are trying to revisit the dye laser, but with a focus on low cost and reusability based on the silicone elastomer process technology and nanoimprint technology. Besides the advantage of the wide emission spectrum of the dye itself, in which the pico-second or even the femto-second lasers could be realized, these lasers are expected to be fully compatible with the current soft-lithographical-defined microfluidic devices. Due to the elastic properties of the skeletal material, they have the unique property of being mechanically tunable. The implementation of these millimeter-scale dye lasers on a microfluidic chip would be very important for making fully functional “lab-on-a-chip” systems for very important applications such as fluorescent analysis in biological and chemical analysis.

1.2 Organization of the thesis

Chapter 2 describes the general fabrication process and laser characteristic measurement setups of the semiconductor nanolasers and the organic dye lasers. This chapter compares the different fabrication techniques, as well as the different equipment available, and gives the practical guidelines for making our nano-scale laser devices. Several important techniques, such as wafer design and epitaxy growth, electron beam lithography, reactive ion beam etching, inductively coupled plasma etching, and membrane formation are described in detail.

Chapter 3 describes the performance of submicron microdisk lasers fabricated within InGaP/InGaAlP quantum well material working at room temperature. The smallest lasers, with diameters of approximately 600 nm, feature ultra-small mode volumes and exhibit single-mode operation at low threshold powers. Their small cavity volumes of approximately 0.03 μm^3 enable microdisk lasers to be used as spectroscopic sources. In this chapter, we demonstrate the fabrication and characterization of visible, monolithically fabricated, submicron microdisk lasers. Also, we demonstrate refractive index monitoring by using these ultra-small lasers, and compare the results with that of photonic crystal lasers.

Chapter 4 describes the fabrication and performance of photonic crystal lasers fabricated within thin membranes of InGaP/InGaAlP quantum well material and emitting in the visible wavelength range. These lasers have ultra-small mode volumes, emit red light, and exhibit low threshold powers. They can be lithographically tuned from 650 – 690 nm. Their cavity volumes of approximately 0.01 μm^3 are ideally suited for use as spectroscopic sources.

In Chapter 5, single-frequency lasing from organic dye solutions on a monolithic poly(dimethylsiloxane) (PDMS) elastomer chip is demonstrated. The laser cavity consists of a single mode liquid core/PDMS cladding channel waveguide, and a phase-shifted 15th order distributed feedback (DFB) structure. 1 mM solution of Rhodamine 6G in a methanol and ethylene glycol mixture was used as the gain medium. Using 6 nanosecond 532 nm Nd:YAG laser pulses as the pump light, we achieved threshold pump fluence of ~0.8 mJ/cm^2 and single-mode operation at pump levels up to ten times the threshold. This microfabricated dye laser provides a compact and inexpensive coherent light source for microfluidics and integrated optics covering the spectral region from near-UV to near-IR.

In Chapter 6, a continuously tunable optofluidic distributed feedback (DFB) dye laser is demonstrated on a monolithic poly(dimethylsiloxane) (PDMS) chip. The optical feedback was provided by a phase-shifted higher order Bragg grating embedded in the liquid core of a single-mode buried channel waveguide. Due to the elastomer nature of PDMS, the tunable output was obtained by mechanically varying the grating period. Nearly 60 nm tuning range from a single chip was achieved with two dye molecules: Rhodamine 6G and Rhodamine 101. Single-mode operation was maintained with less than 0.1 nm linewidth. Because of the higher-order grating, a single laser, when operated with different dye solutions, can provide tunable output covering from near-UV to near-IR spectral region. An array of five DFB dye lasers with different grating periods was also demonstrated on a chip. Such tunable integrated laser arrays are key components in advanced spectroscopy.

Chapter 7 demonstrates an optically pumped, surface emitting, polymer dye laser fabricated by nanoimprint lithography. Our laser is based on an organic dye hosted within a poly(methylmethacrylate) matrix coated on a transparent substrate, and the laser cavity consists of a second-order circular grating distributed feedback structure. Using 6 nanosecond 532 nm Nd:YAG optical pump pulses, laser emission peaked at 618 nm with a linewidth of 0.18 nm and a threshold of 1.31 nJ/mm^2. The nanoimprinted solid-state dye laser geometry described here offers a low cost and compact coherent light source for lab-on-chip spectroscopy systems, a low pump threshold, and geometry well matched to a light emitting diode (LED) pump source. LED-pumped nanoimprinted dye lasers provide an interesting alternative for high-power and portable polymer laser devices.

Chapter 8 describes a mask pattern transferred transient grating (MPT-TG) technique by using metal grating films. Transient thermal grating is generated by an ultraviolet light pattern transfer to nitrobenzene in 2-propanol solution, and the subsequent effect is detected through its diffraction to a probe beam. The thermal diffusion coefficient is obtained by the relationship between the grating periods and the signal decay lifetime, and is well in agreement with the calculated value. This technique has many advantages, such as a simple setting, an easy alignment, accurate phase control, and high stability for molecular-dynamics study in solutions.