Review on recent Developments on Fabrication Techniques of Distributed Feedback (DFB) Based Organic Lasers

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Abstract. To date, the state of art organic semiconductor distributed feedback (DFB) lasers gains tremendous interest in the organic device industry. This paper presents a short reviews on the fabrication techniques of DFB based laser by focusing on the fabrication method of DFB corrugated structure and the deposition of organic gain on the nano-patterned DFB resonator. The fabrication techniques such as Laser Direct Writing (LDW), ultrafast photo excitation dynamics, Laser Interference Lithography (LIL) and Nanoimprint Lithography (NIL) for DFB patterning are presented. In addition to that, the method for gain medium deposition method is also discussed. The technical procedures of the stated fabrication techniques are summarized together with their benefits and comparisons to the traditional fabrication techniques.

1. Introduction

Today, laser become one of the most significant inventions that has been used in all area such as medicine, electronics, computer hardware, technology, communication, and even in the scientific research area. Laser can be defined as a device that produces and amplifies a narrow beam light in a certain defined electromagnetic spectrum region. Laser has its own distinctive properties compared to normal light source like mercury and tungsten lamp as the light waves of laser can travel in longer distance with a very small divergence. To make a laser works, there are three main elements required as shown in Figure 1, namely, gain medium, feedback resonator and excitation source [1]. The gain medium of the laser basically can be a liquid, a solid, or a gas that use the energy level of atoms or molecules to increase the light wave power during its propagation [1]. The gain medium is placed in a resonator and the light repeatedly goes through the gain medium as it bounces back and forth in between the mirrors. The output coupler mirror reflects most of the light, but transmits small portions as the output laser beam [2]. For organic laser, feedback structure is used instead of mirror to make it compatible for the periodic structure of organic gain medium [2,3]. The organic compounds construct a new type of semiconductor electronic materials to be utilized in various applications such as organic light-emitting diodes (OLEDs), organic photovoltaic (PV), thin film transistors (TFTs) organic spin-valve devices as well as optical switches.
Figure 1. A simple laser building block.

The latest developments of organic laser are focusing on the usage of organic materials in photonic device due to its attractive processing capabilities, broad absorption and emission spectra, and high spectral coverage [4,5,6]. In contrary to the inorganic material, less harmful organic material for laser offers the potential of large emission coverage or highly tunable, convenient and inexpensive structure cost [7,8,9]. These advantages could help the organic laser to easily adjust their optical characteristic. “Organic” term in laser is normally used as there is organic gain medium utilized in the structure. In 1992, Moses et al introduced the first organic laser where they demonstrated the laser utilized conjugated polymer as the gain medium [10]. However, to date more examples were demonstrated where both gain medium and the optical feedback structure are both “organic” [11] There are few optical feedback structures that have been demonstrated for organic lasers for example planar cavities [12,13], distributed feedback and photonic crystal structure [14,15], whispering gallery mode resonators [16,17], plasmonic structure [18], organic crystal based cavities and a few more [1,19].

It is observed that organic distributed feedback (DFB) based laser source gained particular interests in the state-of-art organic laser technology [14,15] due to its excellent characteristics such as well-defined directional output [20,21,22], the emitter can be tuned to cover the whole visible spectral range [23], low operating threshold [24], high reflectivity as well as simple fabrication steps. DFB lasers consists of two main features, the feedback mechanism and gain medium are integrated and distributed throughout the structure [25,26]. The optical feedback and the output coupling for this type of laser are achieved via DFB resonator. As shown in Figure 2, this DFB resonator is consists of grating-patterned substrate and the organic gain material is then coated on top of it. This corrugated structure replaced the diffraction grating where the light traveling in one direction will be diffracted in a new direction [1,2]. The maximum coupling between forward and backward propagation along the waveguide produced the light feedback of the laser.

Figure 2 Distributed feedback structure with corrugated substrate and gain medium deposited on top of the substrate.
In term of fabrication, resonator DFB is conventionally formed evaporating using electron beam lithography (EBL). But, even though EBL is well known to be one of the most precise, and versatile methods for nano-patterning, it is a time consuming method, requires high vacuum, as well as advanced control electronics, which makes cost-inefficient to be utilized [27,28,29]. On the other hand, organic gain medium is normally being processed via inexpensive solution process approach for example spin-coating method. However, using this method, the gain material will cover the whole substrate [30-31]. Regardless of the targeted application, the fabrication technology of resonator and gain medium is the paramount important to fully exploiting the potential associated with the organic materials. Thus, suitable solution process approach to produce conjugated polymer is required. To the author’s best knowledge, it is somewhat difficult to find the literatures that summarized all the fabrication techniques available for DFB type of organic laser. Thus, in this paper, the fabrication methods for organic laser using DFB corrugated structure will be presented.

2. Fabrication techniques for DFB corrugated structure

Miniaturized organic laser light sources shown a promising performance when integrated in all-polymer lab on chip and sensing application [29,32-34]. Low-cost fabrication of DFB corrugation nanostructures can be achieved via the fabrication technique that we discuss here. For DFB patterning, we will discuss about four different techniques namely Laser Direct Writing Techniques, Ultrafast Photo Excitation Dynamic Laser, Laser Interference Lithography and Nanoimprint Lithography. We will continue with the deposition method of organic gain in the next section which will cover two different approaches, which are thermal deposition and solution process method.

2.1 Laser Direct Writing Techniques

The first technique is Laser Direct Writing (LDW). This technique is a computer controlled two-dimensional (2D) and three-dimensional (3D) pattern beams by transparent material, causing the two and more photons being absorbed and polymerized locally [35]. The focused UV laser beam pulses pass through multi-photon polymerization (MPP). The beam of ultrafast laser is tightly focused inside the volume of a ribbon support and interacts with an ink coating containing a suspension of the material to be deposited. This technique is depicted as a method using a pulsing laser to create synthetic nano-diamond films and patterns from graphite, with potential applications from biosensors to computer chips [36]. Figure 3 illustrates the process of Laser Direct Writing (LDW).

![Figure 3. Laser Direct Writing (LDW) Process. Adapted from [36].](image)

LDW utilizes laser induced forward transfer to output patterns of complex shapes. It is a
non-lithographic digital microfabrication of microelectronics, which is faster, economical and highly versatile than the convention fabrication method of lithography [37]. It also allows deposition under normal room temperature, high temperature and pressure chamber. It combines the ability of remove ablation, modification and addition controlled using computer aids to process complex and delicate materials in the processes of metal cutting and welding, using the computing technology as a latest method. This method opens a path to new technology such as Scaffold 3D printing [38].

2.2 Ultrafast Photo Excitation Dynamic Laser

Ultrafast photo excitation dynamics of the radical laser is photo excited concentrated laser beam, which were investigated by femtosecond laser spectroscopy. Femtosecond pump probe technique is a powerful tool for the investigation of ultrafast processes in condensed matter [39]. Ultrafast dynamics and the laser action of organic semiconductors is one of the most recent fabrication methods, which involves the laser action in pi-conjugated polymer films, solutions and microcavities [40,41]. In 2D and 3D lasers, ultrafast femtosecond laser is applying the technique of pump probe spectroscopy. The laser pulse is divided into two portions, a stronger beam (pump) for exciting the sample, generating a non-equilibrium state, and a weaker beam (probe) for monitoring the pump-induced changes in the optical reflectivity or transmission. The lasers pulses yield information about the relaxation of electronic states from the time delay between arrivals of pump and probe pulses [42].

2.3 Laser Interference Lithography

Laser Interference Lithography (LIL) or known as holographic lithography become an attractive technique especially for microscale and nanoscale manufacturing. This technology has been used to fabricate photonic crystals slabs (PCS) [43], templates of high-density and periodic structure for Micro-electromechanical Systems (MEMS) [44]. This technique uses mask-less exposure in which uses the interference of two or more electromagnetic waves of the same length with different angle laser beams to form an interference fringe pattern on substrate of photoresist layer. There are critical process parameters that affect the LIL process, which are beam power, exposure dosage, intensity distribution, and angle between beams [45]. The general principle of two-beam LIL is illustrated in Figure 4. In this set-up, the organic semiconductor laser is optically pumped with an operation of 266 nm wavelength by diode pumped solid-state (DPSS). The beam splitter produced two interference beams and directed both beams toward the sample of photoresist layer using rotatable concave mirrors. On the photoresist coating layer, a standing wave is formed at angle $+\theta$ and $-\theta$ thus resulting an interference pattern with a period of $\lambda/2\sin\theta$, where $\lambda$ is the wavelength of operation light [46].

![Figure 4. Two-laser beams interference [46].](image-url)
LIL technology is mostly used for mass production as it offers low cost compared to the other beam technologies, high fabrication resolution compared to other optical technologies, and high processing rate. In the same time, it is able to fabricate large area of pattern which up to hundreds of mm in diameter. LIL also offers high-efficiency for parallel writing technique because it able to fabricate periodic structure by recording the interference pattern on the target material in one step [44]. Furthermore, the faster periodic pattern generation of NIL on the larger area offers the creation of large-size of 2D PCs without losing performance aspect.

2.4 Nanoimprint Lithography
Nanoimprint Lithography (NIL) is another non-conventional lithographic of nanofabrication technique that has been used for mass production and for high-throughput polymer nanostructure patterning at great precision with low costs [44]. Nowadays, there are several techniques of NIL exist such as thermal NIL (hot embossing), UV-assisted NIL, roll-to-roll nanoimprinting [46], and soft lithography [47]. In this technique, NIL creates a replication of patterned mold from a master by mechanical deformation of the polymer layer or the resist material on substrates. The master can be used for multiple times to replicate the pattern into a desired gain medium. One of the inventions by B. Guilhabert et al is on fabrication and characterization of mechanically flexible 4x4 array organic semiconductor laser (OSL) by using soft lithography from a 1-D silica master granting reproduction. This process used blue-emitting tris (trifluorene) truxene oligomers as gain medium. The fabrication process created a grating-on-mesa array structures on the suitable polymer by masking certain area of a 1-D SiO2 master grating with a patterned photoresist (PR) [47]. In addition, NIL can be used in a wide range of applications since it can imprint a structure of functional device especially in electronics, data storage, photonic, and biotechnology [48].

Roller-Nanoimprinting technique is beneficial to fabricate a surface nanorelief large-format nanostructure mass production with higher production rate and lower cost. NIL currently used in production of semi-industrial of photonic and microelectronics device since it can reach ~1 m/min of fabrication speed, which is 104-105 times faster compared to a traditional electron beam (e-beam) lithography. In addition, this technique offers improvement on light absorption, low molecular weight polymers and better control on chain alignment orientation in conjugated crystalline. The device efficiency also increased by 500% when the power conversion efficiencies is set to the optimum value [49].

3. Fabrication techniques for Gain medium deposition
Thus far, the thin film deposition method is the main tool for development of integrated organic lasers that intend at producing a wave-guiding layer of the gain medium on top of low refractive index substrate. This technique is commonly used in fabricating DFB organic laser as this type of laser usually required thin film of less than 200 nm [50]. Among thin film technology available to date are thermal sublimation [51], plasma enhanced chemical vapour deposition (CVD) method [52], pulsed laser deposition (PLD) [53,54], electrospray deposition [55,56], atmospheric-pressure ion deposition [57] matrix-assisted pulsed laser evaporation [58,59] as well as solution process method [60-62]. Among all these technology, the most prevailing one is the solution process, as it is well known to be inexpensive and facile method.

3.1 Solution Process methods
Figure 5 depicts three different low cost solution process approaches namely (a) spin-coating, (b) dip-coating as well as (c) doctor blading for gain material deposition [63]. The thickness of the thin film could be controlled by the solvent concentration, spin speed (for spin coating), spin duration as well as gap height for doctor-blade process. However, the process to control the layer thickness and the film
uniformity is more challenging especially to control the film thickness at the nanometer level as it is a trial and error process where film characterization is required through profilometer or interferometric. In addition to that, via spin-coating or doctor blading, the solvent on top of the corrugated structure may erode the nano-patterned polymer substrate.

As an alternative to this, the lateral control can be achieved using printing techniques such as the use of ink-jet printing.

3.2 Ink-jet printing method
To date, ink jet printing has widely been used in various organic electronic device fabrication [64-66]. This printing method is also been applied in organic laser fabrication in order to achieve an accurate controlled gain medium deposition on top of substrate [67]. It also allows the deposition of few different organic materials to be deposited on to one substrate [68].

In ink jet printing process, a mixture of high boiling and low boiling solvents are utilized for dissolving the polymer to optimize film uniformity. In contrast to solution based deposition technique, ink jet printing allows the deposition of thin films with arbitrary lateral shapes and small lateral dimensions [69] as depicted in Figure 6. Thus, a precise organic gain medium deposited on defined grating trenches could be achieved.
4. Conclusion and Outlook

To date, various organic gain medium for laser has been designed and synthesized to be integrated with the resonators architectures which demonstrate tremendous improvement in spectral properties, lifetime, low operating threshold as well as the improve gains produced. The sizes of laser components are shrunk into smaller scale and the recent fabrication equipment are also smaller, compact, modifiable, and faster in response time. The cyber world has upgraded the organic laser to have higher dimensions with the vitality of computing modeling. The organic laser is an essential optical application in the emerging organic semiconductor field due to its three main reasons, which are smaller in material size, lower in producing and maintenance cost, and increasing demands of high energy organic laser in the field of communication engineering, medical treatment engineering and optical engineering.

In order to fabricate highly efficient, smaller as well as compact organic laser, appropriate fabrication technique must be properly considered. The detailed descriptions on the recent fabrication techniques of the organic laser development are summarized in this paper together with their procedural techniques and advantages over the conventional methods. Although intense research has been made in order to improve the laser fabrication, there are still more challenges to come. More attention should be paid in choosing the fabrication technology for resonator and gain medium fabrication regardless of the targeted applications.

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