PAPER • OPEN ACCESS

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

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

[1]Noor Azrina Talik [2*]Yap Boon Kar, [3] Siti Noradhlia Mohamad Tukijan, [4]Chuan Ling Wong**

[1,2,3,4]Department of Electronic and Communications, College of Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia

*kbyap@uniten.edu.my / **azrina@uniten.edu.my

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.

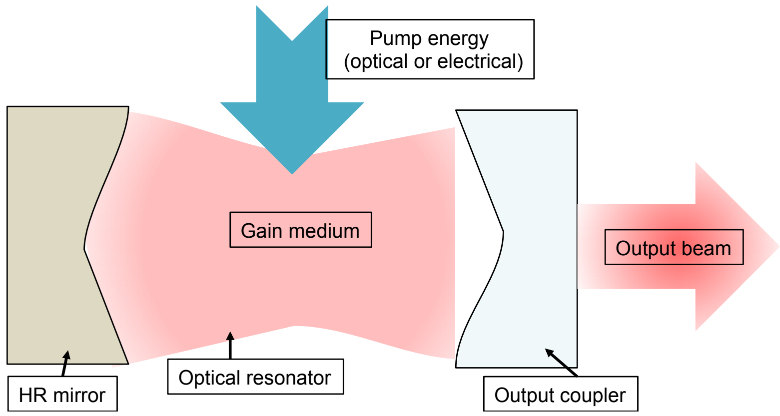

Figure 1. A simple laser building block.

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.

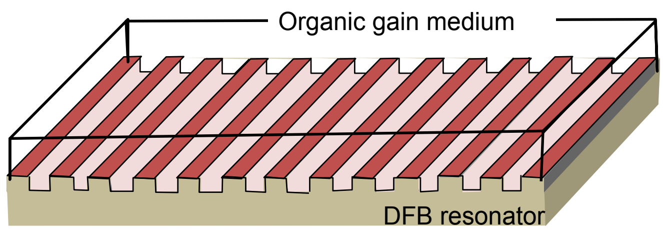

Figure 2 Distributed feedback structure with corrugated substrate and gain medium deposited on top of the substrate.

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).

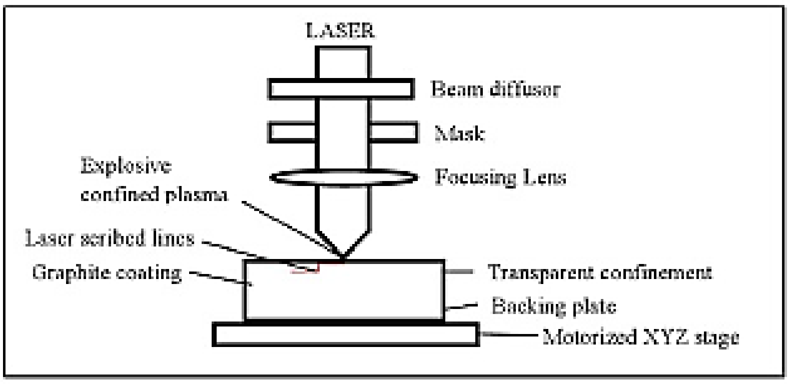

Figure 3. Laser Direct Writing (LDW) Process. Adapted from [36].

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 + θ and – θ thus resulting an interference pattern with a period of $\lambda/2\sin\theta$, where λ is the wavelength of operation light [46].

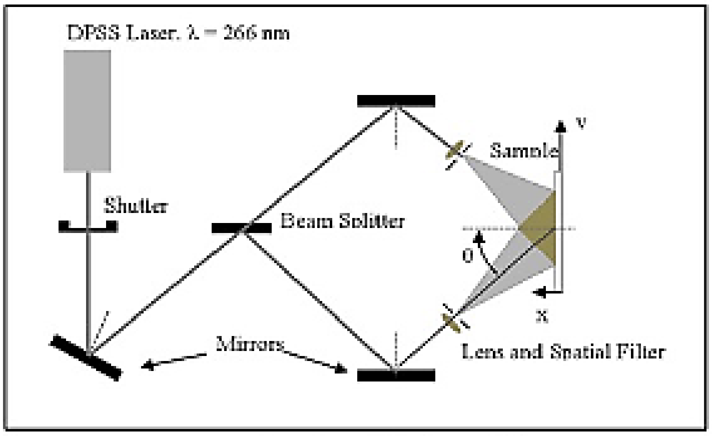

Figure 4. Two-laser beams interference [46].

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 interfermetric. 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.

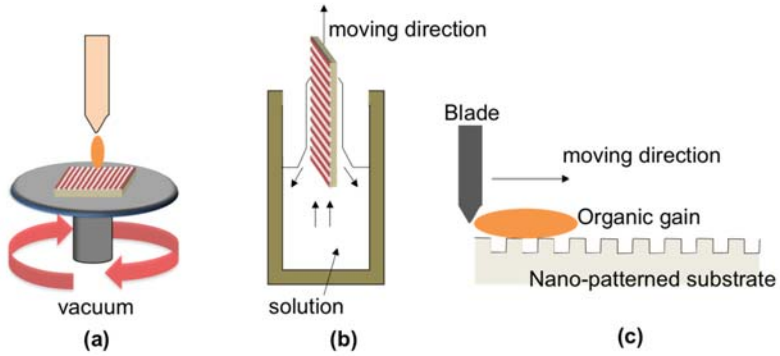

Figure 5. (a) Spin coating, (b) dip coating and (c) doctor blading method.

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.

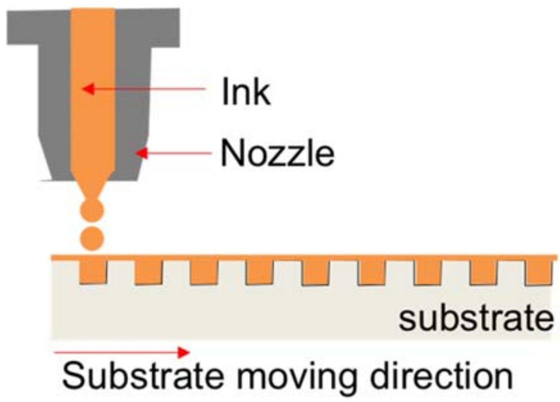

Figure 6 Ink-jet printing technique

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.

References

[1] Chénais S and Forget S 2012 Recent Advances in Solid-State Organic Laser *Polym. Int.* **61** 390-406

[2] Samuel, I.D. and Turnbull, G.A., 2004. Polymer lasers: recent advances. *Materials today*, ***7*** 28-35

[3] Huang, W., Chen, L. and Xuan, L., 2014. Efficient laser emission from organic semiconductor activated holographic polymer dispersed liquid crystal transmission gratings. *RSC Advances* ***4*** (73) 38606-38613.

[4] Foucher C, Guilhabert B, Herrnsd orf J, Laurand N and Dawson M D 2014 Diode-Pumped, Mechanically-Flexible Organic Lasers Fully Encapsulated With Ultra-Thin Glass Membranes *2014 IEEE Photonics Conf.* **3** 536–37

[5] Bettotti, P., 2014. Hybrid materials for integrated photonics. *Advances in Optics* **2014** 1-24

[6] Dong, H., Zhang, C. and Zhao, Y.S., 2017. Host–guest composite organic microlasers. *Journal of Materials Chemistry C.* 1-3

[7] Clark J and Lanzani G 2010 Organic photonics for communications *Nat. Publ. Gr.* **4** 438–446

[8] Bogue R 2011 Developments in organic lasers and their role in sensing *Sens. Rev.* **31** 13–17

[9] Vannahme C, Klinkhammer S, Christiansen M, Kolew A, Kristensen A, Lemmer U and Mappes T 2010 All-polymer organic semiconductor laser chips: parallel fabrication and encapsulation *Opt. Express* **18** 24881–87

[10] Moses, D. (1992). High quantum efficiency luminescence from a conducting polymer in solution—a novel polymer laser-dye. Applied Physics Letters, 60(26), 3215–3216.

[11] Palatnik, A., Bitton, O., Aviv, H. and Tischler, Y.R., 2016. Influence of gain material concentration on an organic DFB laser. *Optical Materials Express*, *6*(9), pp.2715-2724.

[12] Schulzgen, A., Spiegelberg, C., Morrell, M.M., Mendes, S.B., Nabor, M.F., Mash, E.A., Allemand, P.M., Kippelen, B. and Peyghambarian, N., 1998, May. A vertical cavity surface emitting polymer laser. In *Lasers and Electro-Optics, 1998. CLEO 98. Technical Digest. Summaries of papers presented at the Conference on* IEEE 6-7 IEEE

[13] Dodabalapur, A., Berggren, M., Slusher, R.E. and Bao, Z., 1997, November. Design of materials and cavities for organic lasers. In *Lasers and Electro-Optics Society Annual Meeting, 1997. LEOS'97 10th Annual Meeting. Conference Proceedings., IEEE* **2** 171

[14] Baumann, K., Stöferle, T., Moll, N., Raino, G., Mahrt, R.F., Wahlbrink, T., Bolten, J. and Scherf, U., 2010. Design and optical characterization of photonic crystal lasers with organic gain material. *Journal Of Optics*, **12** (6) 065003.
[15] Klein, S., Barsella, A., Stortz, V., Taupier, G., Fort, A. and Dorkenoo, K.D., 2005, June. Photopolymerization techniques for the design of DFB organic lasers. In *Lasers and Electro-Optics Europe, 2005. CLEO/Europe. 2005 Conference on* p.261 IEEE
[16] Zhang, C., Zou, C.L., Yan, Y., Wei, C., Cui, J.M., Sun, F.W., Yao, J. and Zhao, Y.S., 2013. Self□Assembled Organic Crystalline Microrings as Active Whispering□Gallery□Mode Optical Resonators. *Advanced Optical Materials*, **1** (5) 357-361
[17] Melnikau, D., Savateeva, D., Chuvilin, A., Hillenbrand, R. and Rakovich, Y.P., 2011. Whispering gallery mode resonators with J-aggregates. *Optics express*, **19** (22) 22280-22291
[18] Wu, H.Y., Liu, L., Lu, M. and Cunningham, B.T., 2016. Lasing emission from plasmonic nanodome arrays. *Advanced Optical Materials*.
[19] Chakaroun, M., Coens, A., Fabre, N., Gourdon, F., Solard, J., Fischer, A., Boudrioua, A. and Lee, C.C., 2011. Optimal design of a microcavity organic laser device under electrical pumping. *Optics express*, **19**(2) 493-505
[20] Wu, C., Khanal, S., Reno, J.L. and Kumar, S., 2016. Terahertz plasmonic laser radiating in an ultra-narrow beam. *Optica*, **3**(7) 734-740
[21] S.L. Lee, I.F. Jang, C.Y.Wang, C.T. Pein, T.T Shih, 2000 Monolitically integrated multi-wavelength sampled grating DBR lasers for dense WDM applications. *IEE J. Seleced Topics Quant. Electron.* **6** 197
[22] R. Kaiser, F.Fidorra, H.Heidrich, P.Albrecht, W.Rehbein, S.Malchow, H.Schroeter-Janssen, D.Franke, G.Sztefka, 1994, *6th Inter. Conf. on InP and Related Materials* P.474 CA
[23] Klinkhammer, S., Liu, X., Huska, K., Shen, Y., Vanderheiden, S., Valouch, S., Vannahme, C., Bräse, S., Mappes, T. and Lemmer, U., 2012. Continuously tunable solution-processed organic semiconductor DFB lasers pumped by laser diode. *Optics express*, **20**(6)6357-6364
[24] Tsiminis, G., Wang, Y., Shaw, P.E., Kanibolotsky, A.L., Perepichka, I.F., Dawson, M.D., Skabara, P.J., Turnbull, G.A. and Samuel, I.D., 2009. Low-threshold organic laser based on an oligofluorene truxene with low optical losses. *Applied Physics Letters*, **94**(24)165
[25] Shank, C.V., Bjorkholm, J.E. and Kogelnik, H., 1971. TUNABLE DISTRIBUTED□FEEDBACK DYE LASER. *Applied Physics Letters*, **18**(9) 395-396
[26] Aoyagi, Y., Aoyagi, T., Toyoda, K. and Namba, S., 1975. Tunable distributed□feedback dye laser. *Applied Physics Letters*, **27**(12) 687-688
[27] Li, L., Cao, B. and Chen, X. 2014 Demonstration of a low-cost cascade tunable semiconductor DFB laser In *Optical Communications and Networks (ICOCN), 2014 13th International Conference* 1-4
[28] Tsuji, Y., Yanagisawa, M., Yoshinaga, H., Inoue, N. and Nomaguchi, T., 2011. Highly uniform fabrication of diffraction gratings for distributed feedback laser diodes by nanoimprint lithography *Japanese Journal of Applied Physics*, ***50*** (6S) 06GK06
[29] Liu, X., Prinz, S., Besser, H., Pfleging, W., Wissmann, M., Vannahme, C., Guttmann, M., Mappes, T., Koeber, S., Koos, C. and Lemmer, U. 2014. Organic semiconductor distributed feedback laser pixels for lab-on-a-chip applications fabricated by laser-assisted replication. *Faraday discussions*, *174,* 153-164.
[30] Mhibik, O., Chénais, S., Forget, S., Defranoux, C. and Sanaur, S., 2016. Inkjet-printed vertically emitting solid-state organic lasers. *Journal of Applied Physics*, **119** (17) 173101.
[31] Wan, W., Huang, W., Pu, D., Qiao, W., Ye, Y., Wei, G., Fang, Z., Zhou, X. and Chen, L., 2015. High performance organic distributed Bragg reflector lasers fabricated by dot matrix holography. *Optics express*, **23**(25) 31926-31935
[32] Llobera, A., Juvert, J., González-Fernández, A., Ibarlucea, B., Carregal-Romero, E., Büttgenbach, S. and Fernández-Sánchez, C., 2015. Biofunctionalized all-polymer photonic lab on a chip with integrated solid-state light emitter. *Light: Science & Applications*, **4**(4), e271.

[33] Williams, G., Backhouse, C. and Aziz, H., 2014. Integration of organic light emitting diodes and organic photodetectors for lab-on-a-chip bio-detection systems. *Electronics*, **3**(1) 43-75.
[34] Mappes, T., Lenhert, S., Kassel, O., Vannahme, C., Schelb, M. and Mohr, J., 2008, July. An all polymer optofluidic chip with integrated waveguides for biophotonics. In *IEEE/LEOS Summer Topical Meetings, 2008 Digest of the* (pp. 215-216). IEEE.
[35] Häfner M, Pruss C and Osten W 2011 Laser direct writing recent developments for the making of diffractive optics *Opt. & Photonik* **4** 40–43
[36] Nian Q, Wang Y, Yang Y, Li J, Zhang M Y, Shao J, Tang L and Cheng G J 2013 Direct laser writing of nanodiamond films from graphite under ambient conditions *Scientific Report* **4** 6612
[37] Selimis A, Mironov V and Farsari M 2015 Direct laser writing: Principles and materials for scaffold 3D printing *Microelectronic Engineering* **132** 83-89
[38] Rekstyte, S., Balciunas, E., Baltriukiene, D., Rutkunas, V., Bukelskiene, V., Gadonas, R. and Malinauskas, M., 2013, May. Direct laser fabrication of composite material 3D microstructured scaffolds. In *Lasers and Electro-Optics Europe (CLEO EUROPE/IQEC), 2013 Conference on and International Quantum Electronics Conference* (pp. 1-1). IEEE.
[39] Horn W, Kroesen S and Denz C 2014 Two-photon fabrication of organic solid-state distributed feedback lasers in rhodamine 6G doped SU-8 *Appl. Phys. B Lasers Opt.* **117** 311–315
[40] Vardeny Z V 2009, *Ultrafast Dynamics and Laser Action of Organic Semiconductors* (Boca Raton: CRC Press)
[41] Agranovich V M and Leo K **177** 177–178
[42] Shah, J., 2013. *Ultrafast spectroscopy of semiconductors and semiconductor nanostructures* (Vol. 115). Springer Science & Business Media.
[43] Abrams N, Mallouk T E, Divliansky I and Mayer T S 2006 Fabrication of TiO 2 -Organic Hybrid Dot Arrays Using Nanosecond Laser Interference Lithography *the American Ceramic Society* **3510** 3507–10
[44] Liu Q, Duan X and Peng C 2014 *Novel Optical Technologies for Nanofabrication* (New York: Springer)
[45] Seo J, Park J H, Ma Z, Choi J and Ju B 2014 Nanopatterning by laser interference lithography: applications to optical devices *Journal of Nanoscience and Nanotechnology* ***14*** (2) 1521-32
[46] Liu X 2015 *Organic Semiconductor Lasers and Tailored Nanostructures for Raman Spectroscopy* KIT Scientific Publisher.
[47] Guilhabert B, Laurand N, Herrnsdord J, Chen Y, Kanibolotsky A L, Orofino C, Skabara P J and Dawson M D 2012 Mechanically flexible organic semiconductor laser array *IEEE Photonics Journal* ***4*(3)** 684-690
[48] Wang Y 2014 *Low Threshold Organic Semiconductor Lasers: Hybrid Optoelectronics and Applications as Explosive Sensors* (New York: Springer) Chapter 2 9-29
[49] Comoretto D 2015 *Organic and Hybrid Photonic Crystals* (New York: Springer) 303–320
[50] Andrews, J.H., Crescimanno, M., Singer, K.D. and Baer, E., 2014. Melt□processed polymer multilayer distributed feedback lasers: Progress and prospects. *Journal of Polymer Science Part B: Polymer Physics*, **52**(3) 251-271
[51] Berggren, M., Dodabalapur, A., Slusher, R.E. and Bao, Z., 1997. Light amplification in organic thin films using cascade energy transfer. *Nature*, **389** (6650) 466-469
[52] Kozlov, V.G., Parthasarathy, G., Burrows, P.E., Forrest, S.R., You, Y. and Thompson, M.E., 1998. Optically pumped blue organic semiconductor lasers. *Applied physics letters* **72** (2) 144-146
[53] Meier, M., Mekis, A., Dodabalapur, A., Timko, A., Slusher, R.E., Joannopoulos, J.D. and Nalamasu, O., 1999. Laser action from two-dimensional distributed feedback in photonic crystals. *Applied Physics Letters* **74**(1) 7-9
[54] Gill, D.S., Anderson, A.A., Eason, R.W., Warburton, T.J. and Shepherd, D.P., 1996. Laser operation of an Nd: Gd3Ga5O12 thin□film optical waveguide fabricated by pulsed laser deposition. *Applied physics letters*, **69**(1) 10-12

[55] Ju, J., Yamagata, Y. and Higuchi, T., 2009. Thin□Film Fabrication Method for Organic Light□ Emitting Diodes Using Electrospray Deposition. *Advanced Materials*, **21**(43) 4343-4347
[56] Chrisey, D.B., Pique, A., McGill, R.A., Horwitz, J.S., Ringeisen, B.R., Bubb, D.M. and Wu, P.K., 2003. Laser deposition of polymer and biomaterial films. *Chemical Reviews*, **103**(2) 553-576
[57] Saf, R., Goriup, M., Steindl, T., Hamedinger, T.E., Sandholzer, D. and Hayn, G., 2004. Thin organic films by atmospheric-pressure ion deposition. *Nature materials*, **3**(5) 323-329
[58] Wu, P.K., Ringeisen, B.R., Callahan, J., Brooks, M., Bubb, D.M., Wu, H.D., Piqué, A., Spargo, B., McGill, R.A. and Chrisey, D.B., 2001. The deposition, structure, pattern deposition, and activity of biomaterial thin-films by matrix-assisted pulsed-laser evaporation (MAPLE) and MAPLE direct write. *Thin Solid Films*, **398** 607-614
[59] Piqué, A., Wu, P., Ringeisen, B.R., Bubb, D.M., Melinger, J.S., McGill, R.A. and Chrisey, D.B., 2002. Processing of functional polymers and organic thin films by the matrix-assisted pulsed laser evaporation (MAPLE) technique. *Applied Surface Science*, **186** 1 408-415
[60] Navarro-Fuster, V., Calzado, E.M., Boj, P.G., Quintana, J.A., Villalvilla, J.M., Díaz-García, M.A., Trabadelo, V., Juarros, A., Retolaza, A. and Merino, S., 2010. Highly photostable organic distributed feedback laser emitting at 573 nm. *Applied Physics Letters*, **97**1(7) 171104
[61] Turnbull, G.A., Andrew, P., Jory, M.J., Barnes, W.L. and Samuel, I.D.W., 2001. Relationship between photonic band structure and emission characteristics of a polymer distributed feedback laser. *Physical Review B*, **64** (12) 125122.
[62] Heliotis, G., Xia, R., Turnbull, G.A., Andrew, P., Barnes, W.L., Samuel, I.D.W. and Bradley, D.D., 2004. Emission Characteristics and Performance Comparison of Polyfluorene Lasers with One□ and Two□Dimensional Distributed Feedback. *Advanced Functional Materials*, **14**(1) 91-97
[63] Diao, Y., Shaw, L., Bao, Z., & Mannsfeld, S. C. (2014). Morphology control strategies for solution-processed organic semiconductor thin films. *Energy & Environmental Science*, **7** (7), 2145-2159.

[64] Calvert, P., 2001. Inkjet printing for materials and devices. *Chemistry of materials*, **13** (10) 3299-3305.
[65] Rogers, J. and Katz, H., 1999. Printable organic and polymeric semiconducting materials and devices. *Journal of Materials Chemistry* **9** (9) 1895-1904
[66] Rigas, G.P., Payne, M.M., Anthony, J.E., Horton, P.N., Castro, F.A. and Shkunov, M., 2016. Spray printing of organic semiconducting single crystals. *Nature Communications*, *7*.
[67] X. Liu, S. Klinkhammer, K. Sudau, N. Mechau, C. Vannahme, J. Kaschke, T. Mappes, M. Wegener, U. Lemmer 2012 Ink-Jet-Printed Organic Semiconductor Distributed Feedback Laser *Appl. Phys. Express* **5 (7)**, 072101
[68] Geffroy, B., Le Roy, P. and Prat, C. 2006. Organic light□emitting diode (OLED) technology: materials, devices and display technologies. *Polymer International* **55**(6) 572-582
[69] Tekin, E., Holder, E., Kozodaev, D., & Schubert, U. S. 2007. Controlled Pattern Formation of Poly [2□methoxy□5□(2′□ethylhexyloxyl)–1, 4□phenylenevinylene](MEH–PPV) by Ink□Jet Printing. *Advanced Functional Materials*, **17** 2, 277-284.