Laser-induced periodic surface structures as optical resonators for organic thin-film distributed feedback lasers

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Abstract. Laser-induced periodic surface structures (LIPSS) have received considerable attention due to their potential for micro- and nanostructuring and surface functionalization of various materials. We present a novel application of LIPSS on a glass substrate as distributed feedback (DFB) laser resonators, capable of providing sufficient positive optical feedback to achieve lasing in thin-film waveguides with organic small molecules as a gain medium. The direct femtosecond micromachining allows for easy variation of the periodicity across a broad range of values, including those required to reach 1st Bragg order DFB operation. We investigate several small molecule organic thin-film systems and observe lasing in strong accordance with the underlying periodicities of all photonic structures involved. These results demonstrate the effectiveness of LIPSS as DFB laser resonators and suggest that they could facilitate the integration of organic thin-film media-based lasers and other photonic devices into various integrated photonic systems.

Laser-induced periodic surface structures (LIPSS) are a universal phenomenon observed on virtually any material upon irradiation with a linearly polarized femtosecond laser beam of a specific pulse duration, wavelength, and intensity [1]. Since the discovery of LIPSS, and particularly in recent years with the advent of numerous short-pulse laser light sources, research in the field has significantly intensified. The ability to generate LIPSS in a single-step process provides a simple and effective approach for nanostructuring and surface functionalization, enabling control of the mechanical and optical properties of various materials. The research on LIPSS is driven by the potential for developing new applications in fields such as optics, biomedicine, chemistry, and mechanical engineering [2].

Here, we demonstrate for the first time that laser-induced periodic surface structures on a glass substrate can function as effective distributed feedback (DFB) laser resonators and provide sufficient positive optical feedback to achieve lasing in thin-film waveguides containing organic small molecules as a gain medium. The flexibility provided by femtosecond micromachining enables easy variation of the periodicity over a broad range of values, allowing the use of different diffraction orders down to the first Bragg diffraction order and enabling the resonance frequency to be easily tuned according to the gain spectrum of the organic gain medium.

We investigate various small molecule organic thin-film systems that exhibit optical gain under optical pumping and are thermally evaporated onto glass substrates. Prior to thin-film deposition, the surface of the glass substrate is treated via femtosecond laser micromachining in the direct writing regime, as illustrated in the SEM image in the inset of Fig. 1a). A raster-type scanning method is employed, with the sample being moved physically from left to right while maintaining a pitch distance of 760 nm between adjacent scan lines. The polarization state of the light is selected such that laser-induced periodic surface structures form perpendicular to the scan lines. To ensure the formation of high-quality LIPSS ripples with the desired periodicities and minimal phase variations among LIPSS groups, specific parameters such as the excitation wavelength, light intensity, and number of impinging pulses are carefully chosen. By doing so, LIPSS gratings with a dominant periodicity of 182 nm are formed. This approach yields a crossed grating system, in which both gratings can contribute to the lasing. The sample also includes untreated areas for reference measurements.

Figure 1a) shows the emission spectra obtained from a 400 nm thick layer of Alq3:DCM, deposited on a glass substrate by thermal evaporation. This layer thickness supports lower order waveguiding modes along the slab, around the wavelength of 620 nm where the maximum of the Alq3:DCM gain spectrum is observed. The emission spectrum from the untreated area (corresponding to the plane waveguide regime) remains in the linear emission regime (photoluminescence emission below the lasing threshold) and does not exhibit features of lasing or amplified spontaneous emission, owing to the absence of positive optical feedback. In contrast, the emission from the micromachined areas displays two spectrally sharp peaks, whose intensity exhibits a strongly nonlinear behavior as a function of pump power. These peaks are
attributed with high confidence to 3rd Bragg order distributed feedback lasing from the raster-scan grating (with a peak at 623 nm), and to 1st Bragg order DFB lasing from the LIPSS grating (with a peak at 597 nm). The assignment of these peaks is supported by our finite-difference time-domain (FDTD) simulations, which account for the precise system geometry and optical constants. The calculated expected resonance positions are marked in Fig. 1a) by dotted lines and are in good agreement with experimental observations.

In summary, we report on the first demonstration that laser-induced periodic surface structures on glass substrates can function as effective distributed feedback laser resonators, providing enough positive optical feedback to achieve lasing in thin-film waveguides containing organic small molecules as a gain medium. It involves direct femtosecond laser micromachining to create LIPSS ripples on glass substrates. This approach allows for easy variation of the periodicity across a broad range of values, including those required to reach 1st Bragg order DFB operation. Our results demonstrate the effectiveness of LIPSS as DFB laser resonators and suggest their potential use in integrating thin-film organic media-based lasers and other photonic devices into various integrated photonic systems.

References