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Fabrication of high-Q microresonators in dielectric materials using a femtosecond laser: Principle and applications

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ABSTRACT

Femtosecond laser micromachining has been a promising technique for fabricating three-dimensional (3D) micro/nano-structures in various kinds of dielectric materials with unprecedented spatial resolutions as well as flexibility in terms of the geometry and the materials can be processed. This unique capability opens opportunities for fabrication of 3D high-quality (Q) microresonators, which are one of the key elements in modern photonic applications. Here, we review the recent progress in fabrication of high-Q microresonators on glass and crystalline substrates by employing femtosecond laser direct writing. We demonstrate the applications of the fabricated microresonators in generating low-threshold lasers, high-sensitivity chemical sensing and nonlinear optical wavelength conversion.

1. Introduction

High quality (high-Q) factor whispering gallery mode (WGM) microresonator can confine light field for a long period of time within an extremely small volume via total internal reflection along the periphery, thus the WGM microresonators can dramatically boost the strength of light field, thereby promoting the nonlinear interaction between the light and the resonator material [1]. So far, the microresonators have shown to be outstanding candidates for a wide range of applications, such as cavity quantum electrodynamics (c QED) [2–4], nonlinear optics [5–7], optomechanics [8–10], low threshold microlaser [11–14], nonclassical light sources [15–17] and high-sensitivity biosensing [18–20].

Currently, on-chip microresonators are typically fabricated based on planar semiconductor lithography approach followed by either dry or wet etching [21–23]. Although the planar photolithography is extremely successful due to its high precision, high efficiency and cost-effectiveness, this technique does not allow to form three-dimensional (3D) microstructures of arbitrary geometries. Furthermore, many nonlinear optical materials are incompatible with the photolithography mainly due to lack of efficient etching methods. To overcome the difficulties, it is desirable to develop new fabrication technologies.

In the past two decades, femtosecond laser has emerged as a promising tool for high-precision 3D micro/nano-processing of a broad variety of dielectric materials. Since mid-90s, femtosecond laser micromachining has been used to fabricate functional microstructures ranging from microfluidics, microphotonics to micromechanics [24–29]. In 2012, the advancement of the technique has led to the first demonstration of fabrication of microresonators of 3D geometries in fused silica substrate with Q-factors above 10^6 [30]. Since then, utilizing such a technique to fabricate microresonators has been under rapid development [31–33]. Very recently, high-Q microresonators with sub-100 μm diameters have been achieved on crystalline materials including lithium niobate and calcium fluoride, opening the possibility to realize on-chip nonlinear optical processes with unprecedented conversion efficiencies [34–38].

It is worth mentioning that in addition to the inorganic materials such as glass and crystals, WGM microresonators have also been fabricated in polymers using femtosecond laser two-photon

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polymerization [39–44]. Generally speaking, polymers are easier to be processed than dielectric materials, however, they usually suffer from an inferior optical properties such as narrower transmission windows, higher optical absorption losses and lower damage thresholds. Therefore, the choice of material for a microresonator strongly depends on the application. Specifically, for most nonlinear optical applications, inorganic materials, particularly dielectric crystals, are more suitable as the substrate materials for construction of high-Q WGM microresonators.

In this paper, we review the recent progress in fabrication of the high-Q WGM microresonators in dielectric materials using a femtosecond laser as well as the applications of the fabricated devices for low-threshold microlasers, refractive index sensing, and phase-matched second harmonic generation. We begin by introducing the fundamental principle and the typical experimental setup of femtosecond laser micromachining in Sections 2 and 3, respectively. Then, fabrication of high-Q microresonators in glass and crystals are described in great detail in Sections 4 and 5, respectively. Section 6 discusses integration of the microresonators with microfluidics and microelectrodes for building functional microsystems. At last, we summarize the major results and give the future perspectives of this active field of research.

2. Principle of femtosecond laser 3D micromachining

Femtosecond laser has been proved to be a useful tool for micromachining in a large range of materials, such as metals, ceramics, soft materials (e.g., polymers and biotissues), and particularly brittle materials (e.g., glasses and crystals). Compared with traditional material processing using continuous wave (CW) lasers or lasers with longer pulses, femtosecond laser micromachining has the unique 3D fabrication capability in transparent materials thanks to nonlinear absorption mechanisms involving multiphoton absorption and/or tunneling ionization, etc. [45].

When shining light on a dielectric material as illustrated in Fig. 1, linear single photon absorption occurs from the surface of the transparent medium when the incident photon energy is higher than its bandgap, thus it does not allow for internal modification without damage of the surface. However, for intense ultrafast laser pulses at the wavelengths that are transparent to the medium, the electron in the valence band can only be excited to conduction band by multiphoton absorption which occurs only at the focus [46,47]. This is due to the nonlinear dependence of the absorption efficiency on the peak intensity of the laser. The multiphoton absorption intrinsically enables 3D micromachining in transparent materials since there is no out-of-focal absorption in the laser irradiation region.

It should be noted that the physical mechanism mentioned above is applicable for almost all of the transparent materials irradiated by the femtosecond laser, making the technique intrinsically material insensitive.

3. Experimental setup of femtosecond laser micromachining

Fig. 2 schematically illustrates the typical experimental setup. The main components of the system are a femtosecond laser source, a beam control/shaping system, a microscope objective or an aspherical lens for producing a tightly focused spot, and a high-precision XYZ translation stage controlled by a computer for 3D translation of the sample [48].

To control the laser parameters including the pulse width, pulse energy, and pointing direction during fabrication process, a beam control/shaping system is often installed after the laser source, as shown in Fig. 2. To control the pulse energy, a $\lambda/2$-plate combined with a Glan prism is inserted for coarsely varying the laser power as the tunable attenuator while an additional variable

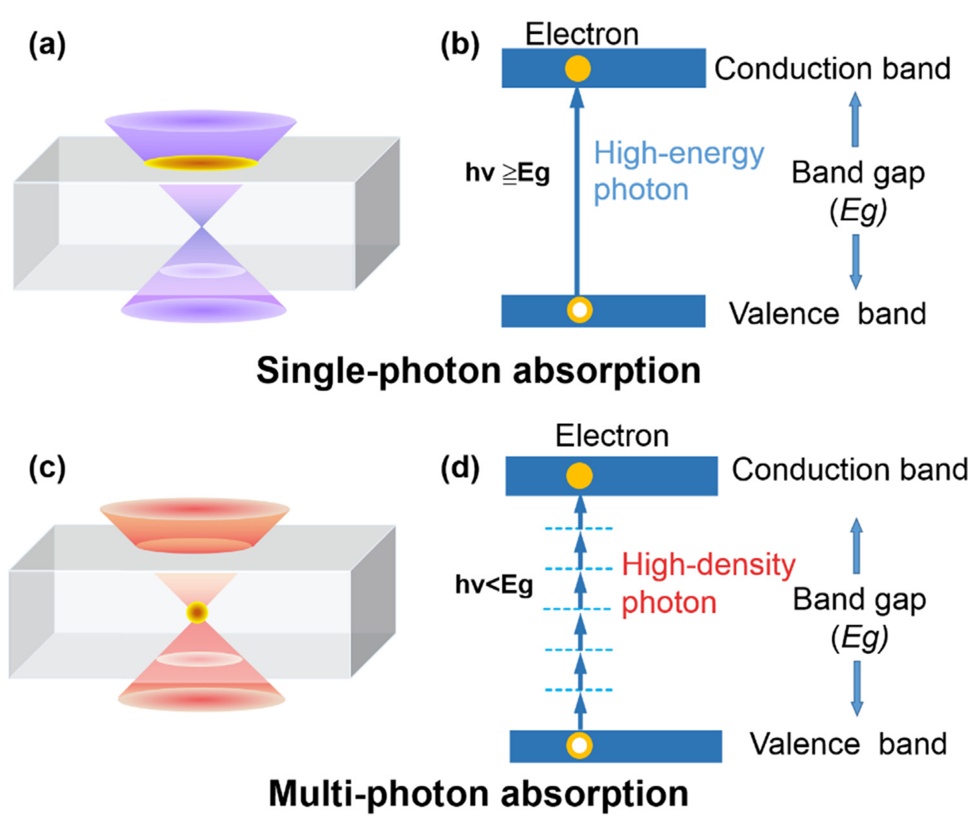

Fig. 1. Sketches of laser processing in transparent materials by (a) single- and (c) multi-photon absorption and their corresponding electron excitation processes are presented in (b) and (d), respectively.

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