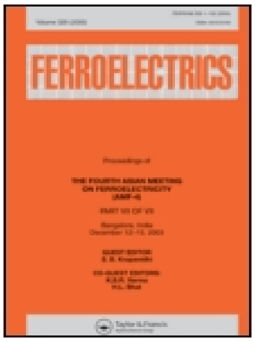

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ISSN: 0015-0193 (Print) 1563-5112 (Online) Journal homepage: http://www.tandfonline.com/loi/gfer20

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To cite this article: Dongshi Zhang , Feng Chen , Jianzhang Shi , Hewei Liu , Hong Wang , Jinhai Si & Xi Yao (2009) Fabrication of Periodic Microholes in $BiNbO_4$ by Femtosecond Laser Pulses for the Applications of 2D Photonic Crystal Waveguide, Ferroelectrics, 387:1, 130-136, DOI: 10.1080/00150190902966628

To link to this article: http://dx.doi.org/10.1080/00150190902966628

Published online: 20 Sep 2010.

Ferroelectrics, 387:130–136, 2009

ISSN: 0015-0193 print / 1563-5112 online
DOI: 10.1080/00150190902966628

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Fabrication of Periodic Microholes in $BiNbO_4$ by Femtosecond Laser Pulses for the Applications of 2D Photonic Crystal Waveguide

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This paper presents the fabrication of periodic microholes arrays in $BiNbO_4$ by femtosecond laser ablation. A circular microhole drilling method was introduced. The relationships between microhole appearance and laser microprocessing parameters have been researched in details, and the ablation parameters were optimized to meet the needs of fabrication of periodic microholes. A two-dimensional photonic crystal waveguide consisting of periodic microholes in $BiNbO_4$ was achieved.

Keywords Femtosecond laser; microholes; BiNbO4; two-dimensional photonic crystal

Introduction

$BiNbO_4$ ceramics is a novel dielectric composite for microwave (MW) frequency region. It has superior physical properties such as high dielectric constant ($\varepsilon' \cong 43$), low dielectric loss, high quality factor ($Q \approx 4000$) and small temperature coefficient of resonant frequency, all of which strongly in favor of its utility as MEMS devices including resonator, filter, dielectric substrate, dielectric antenna, dielectric waveguide circuit, etc [1, 2]. The waveguide devices based on the photonic crystals (PCs) structure, have attracted much attentions [3] due to the existence of photonic band gap (PBG) and unusual dispersion relations for the propagating light. The PCs are periodic microstructures like arrayed microholes. The precise process of periodic microholes is critical for the successful fabrication of PCs structure. A variety of technologies have been applied to fabricate photonic crystals over the past two decades, such as semiconductor lithography [4], self-assembling [5], and holographic lithography [6–10]. However, these technologies are hard to meet the following demands: high accuracy, low cost, and simple machining.

Based on femtosecond laser ablation, laser direct-write processing using precise Computerized Numerical Control (CNC) motion system provides a quick and efficient means

Received November 1, 2008; in final form February 5, 2009.
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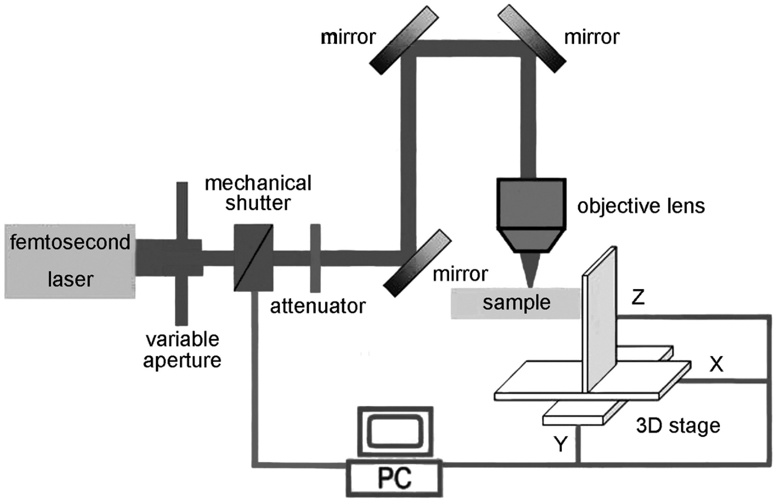


Figure 1. The schematic of the experimental set up.

which could be applied to fabricate different kinds of materials without expensive masks, thus offering a simple, low cost, and flexible micromachining technique, and enables us to fulfill the microhole fabrication with small and fine features. Up to now, femtosecond laser has been widely used to the fabrication of microholes in different materials, such as metals [11–13], transparent material [14], etc, but seldom in ceramics.

In this paper, a circular microhole drilling method was introduced. The relationships between microhole appearance and laser microprocessing parameters have been researched, and the process parameters were optimized to meet the needs of fabrication of periodic microholes. A two-dimensional photonic crystal waveguide consisting of periodic microholes in $BiNbO_4$ was achieved.

Experimental

The experimental setup is shown in Fig. 1. The laser source was a Ti: sapphire oscillator-amplifier system (FEMTOPOWER Compact Pro, Austria), which delivered 800 nm, 30 fs Gaussian laser pulses at a repetition rate of 1 kHz. A mechanical shutter was utilized to turn the laser beam on and off. The incident laser power was adjusted by a neutral density (ND) attenuator. A 5× microscope objective (Nikon, NA = 0.15) focused the laser beam onto the sample. The sample ($BiNbO_4$ ceramic, 5 × 5 × 1 mm) was mounted on a precision computer-controlled x-y-z translation stage with step resolution of 50nm and a maximum speed of 1000 μm/s. A Confocal Microscope (VK-9700, KEYENCE) and an Optical Microscope (LV100D, Nikon) were used to measure and characterize the fabricated microholes. The sample was immersed and treated in ultrasonic bath in water for 30 minutes at 40° before and after laser processing.

Results and Discussion

Figure 2 shows the schematic illustration of the matrix microholes ablation technique. Each microhole is drilled by a multiple circular paths trepanning method. The axial distance

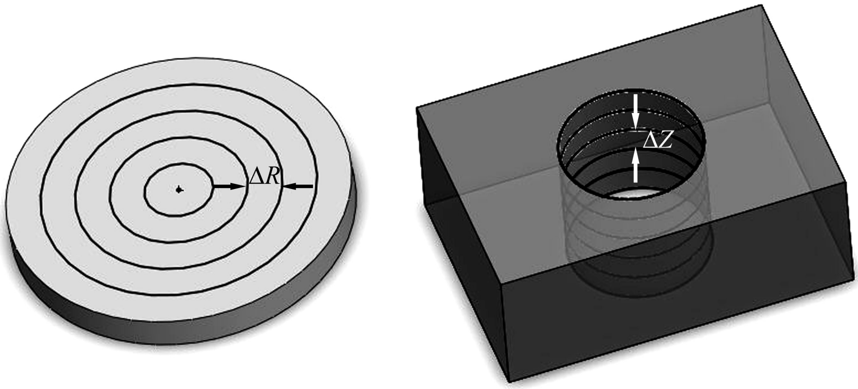


Figure 2. Schematic illustration of the matrix microholes ablation by a multiple circular paths trepanning method.

between consecutive paths is ΔR. A microhole is achieved by a layer-by-layer process with the layer-layer distance ΔZ. The two parameters, ΔR and ΔZ play important roles in the process of the microholes in $BiNbO_4$ ceramic. Usually, the smaller the step distance, the higher microhole quality will be. But it will lower the efficiency of drilling microholes apparently.

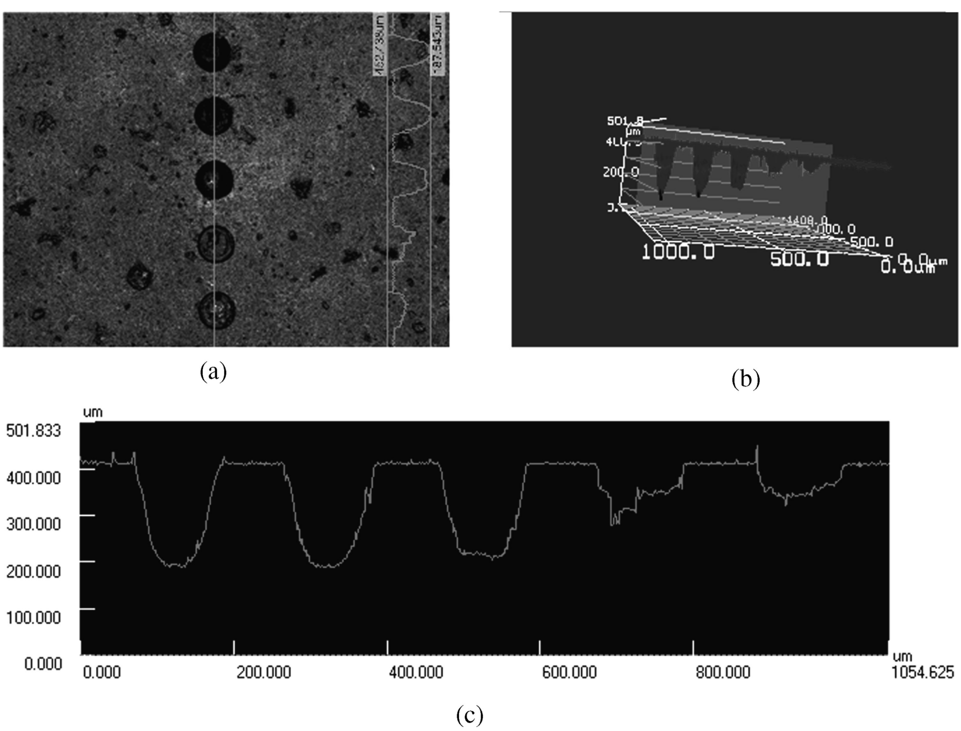


Figure 3. Optical micrograph of the microholes drilled in $BiNbO_4$ ceramic at laser power intensity of 0.06×10^6 W/cm^2, scanning velocity of 100 μm/s, ΔZ of 20 μm and ΔR of 2, 4, 8, 16 and 32 μm, from top to bottom. (b) Three-dimensional image of the microholes. (c) The cross section image of the microholes along the white reference line.

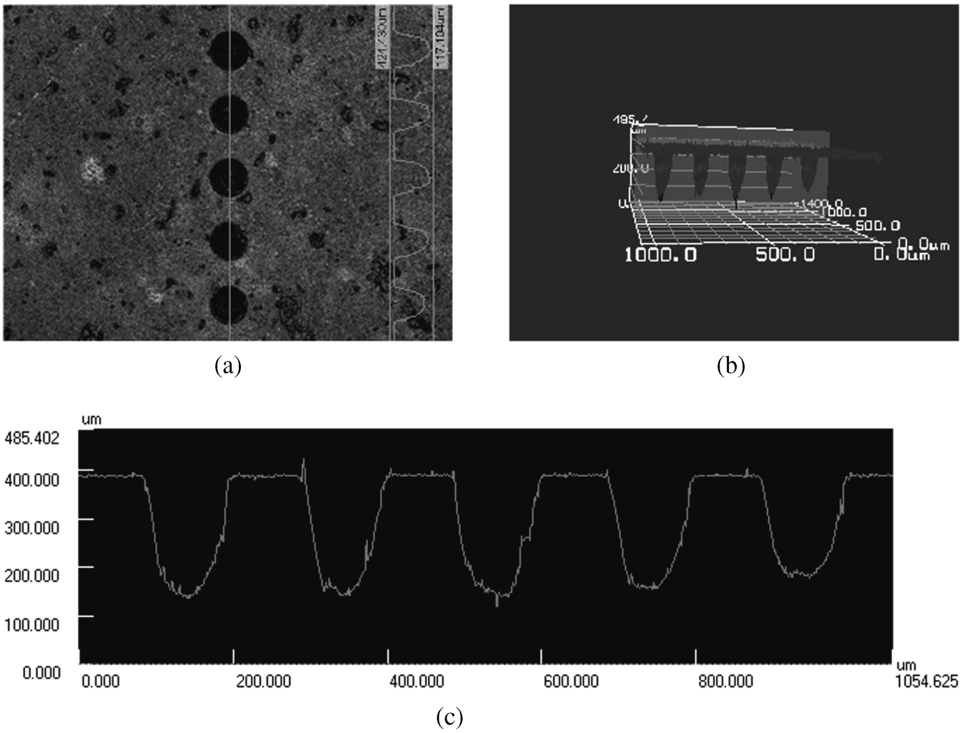


Figure 4. (a) Optical micrograph of microholes drilled in $BiNbO_4$ ceramic at laser power density of 0.06×10^6 W/cm^2, scanning velocity of 100 μm /s, ΔR of 8 μm and ΔZ of 5, 10, 15, 20 and 25 μm, from top to bottom. (b) Three-dimensional image. (c) The cross section image.

Considering both accuracy and machining efficiency, the laser power density and scanning speed were set at 0.06×10^6 W/cm^2 and 100 μm/s, respectively. Under such a condition, the width and depth of micro-groove ablated by laser were 32 μm and 34 μm, respectively. To achieve the optimized process parameters, a number of microholes were fabricated in a $BiNbO_4$ sample with different ΔR and ΔZ as seen in Figs. 3 and 4. The axial step distance ΔR increased from top to bottom, with ΔR of 2, 4, 8, 16 and 32 μm (Fig. 3a). Figure 3b and 3c show that the depths of the microholes would be shallower than we expected as ΔR was equal to or more than half of the width of micro-groove, while as ΔR was less than or equal to a quarter of the width of micro-groove the depths of the microholes would be close to our design. The results show that if the value of ΔR was too large, laser beam would not reach the designed microhole bottom due to the cone conformation of micro-groove, which in some cases hindered the drilling process. As ΔR was less than or equal to quarter of the width of micro-groove, the depths of the microholes were almost identical. As a result, ΔR should be equal to a quarter of the width of groove. With a similar procedure, a couple of tests were achieved to optimize the value of ΔZ (Fig. 4). It indicates ΔZ should be nearly equal to the half of the depth of groove.

As shown in Fig. 5, a series of microholes were also drilled using the optimized parameters of $\Delta R = 8$ μm and $\Delta Z = 15$ μm with different scanning velocities : 100, 200, 400 and 800 μm/s. It presents that the results are very close in different scanning velocities,

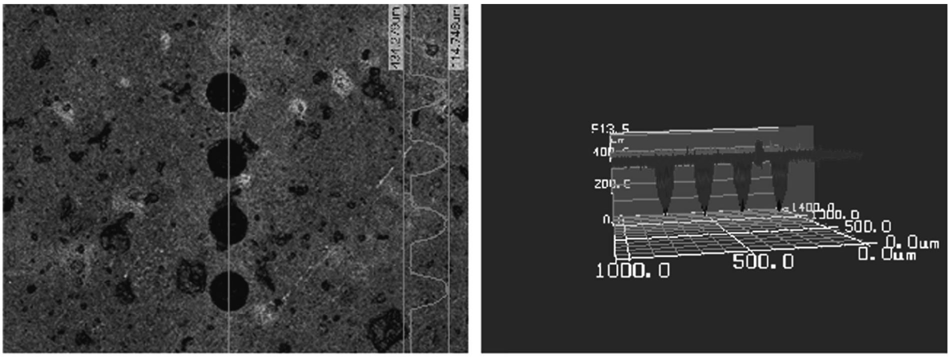


Figure 5. (a) Optical micrograph of microholes in $BiNbO_4$ ceramic drilled at laser power density of 0.06×10^6 W/cm^2, ΔR of 8 μm, ΔZ of 15 μm, and scanning velocities of 100, 200, 400 and 800 μm/s, from top to bottom. (b) Three-dimensional image.

which due to the high ablation rate we used. But the higher the scanning velocity, the more debris would accumulate around the edges of the microholes which would hinder the drilling procession of the adjacent holes. So the scanning velocity was set at 100 μm/s.

Figure 6 shows the width and depth of grooves ablated by femtosecond laser as a function of the laser power density at a scanning velocity of 100 μm/s. With increasing laser power, both the width and depth of groove were increased. The width and depth of groove could be easily changed by careful adjustment of laser power intensity.

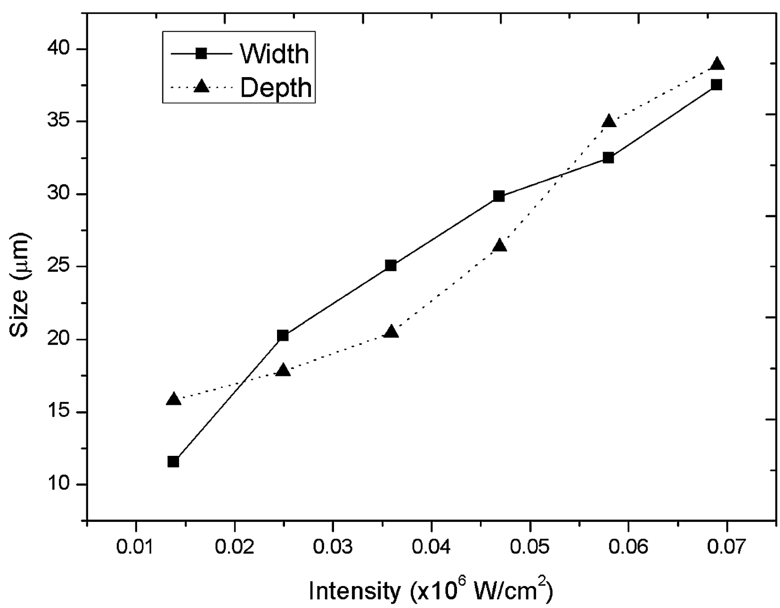
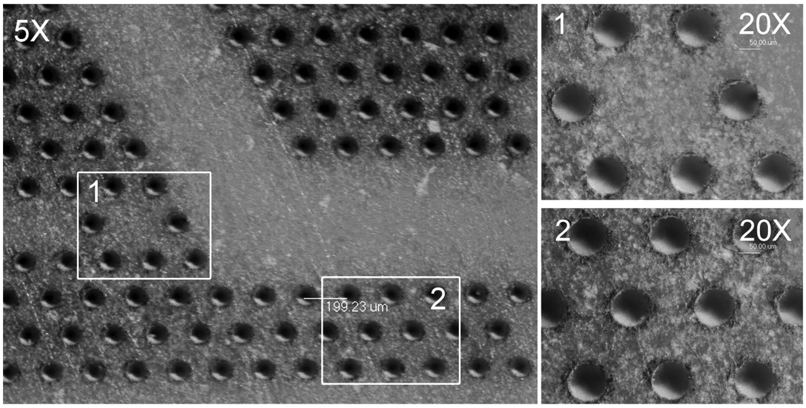
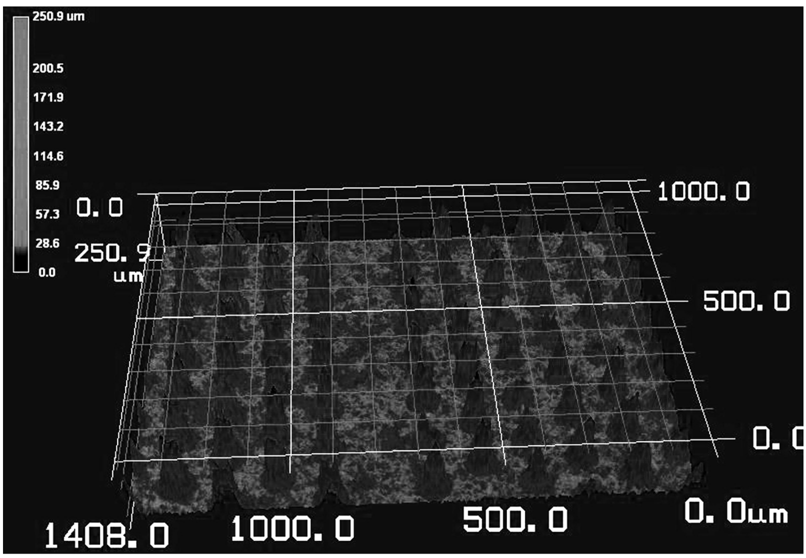


Figure 6. Dependence of the width and depth of micro-grooves on the laser power density at the scanning velocity 100 μm/s.



(a)



(b)

Figure 7. A 2D PCs band waveguide in high permittivity microwave ceramic $BiNbO_4$ was fabricated with laser power density of 0.06×10^6 W/cm^2, scanning speed of 100 μm/s, ΔR of 8 μm and ΔZ of 15 μm. (a) Optical microscope image of the top view. (b) Three-dimensional image of the microholes taken by Confocal Microscope (VK-9700, KEYENCE).

A 2D PCs band waveguide in high permittivity microwave ceramic $BiNbO_4$ was fabricated (Fig. 7). The photonic crystal structure was designed as a waveguide splitter. Three rows of microholes were skipped to form the band waveguide. Meanwhile, a straight waveguide was made by a defect line (one row of missing microholes) coupled with a resonant cavity (one leaving microhole on the defect line). The periodic distance of the arrayed microholes was 200 μm, and the diameter of each microhole was 80 μm. The microholes were highly consistent and the edge of the microholes was smooth without obviously melting region.

Conclusion

The effects of the femtosecond laser machining parameters such as scanning speed, ΔR and ΔZ on the microholes quality were investigated and the process parameters were optimized. A 2D PCs band waveguide in high permittivity microwave ceramic $BiNbO_4$ was fabricated with optimized parameters of laser power density of 0.06×10^6 W/cm^2, scanning speed of 100 μm/s, ΔR of 8 μm and ΔZ of 15 μm. This work demonstrates the suitability and effectiveness of the femtosecond laser microfabrication technology for prototyping PCs band waveguide devices.

Acknowledgments

The authors gratefully acknowledge the financial support for this work provided by the National Science Foundation of China under the Grant Nos. 60678011 and 10674107.

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