Direct-Write Microfabrication for Enhancement of Functionality of Optical Fiber Devices

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ABSTRACT

The improvement of the functionality of optical fiber devices has always been a research topic. In this regard, coating of optical fibers with metal thin films has been considered as an effective approach. We report the deployment of a laser-based direct printing method for pattering of optical fiber Bragg gratings with metal thin films to enhance their functionality. The drop-on-demand and layer-by-layer deposition features of the direct printing methods enable patterning of fibers with customized thicknesses. Using our patented technology, we have established a manufacturing setup for customized pattering of metal thin films on optical fibers. The manufacturing process involves direct printing of nano-particles of metals, e.g., silver, followed by laser sintering. The sintering of nano-particles is associated with atomic diffusion between particles which is controlled by the temperature increase generated by the laser radiation. We have succeeded in depositing silver thin films with thickness ranging from 500 nm to 10 um on optical fibers with 125 um diameter. We have studied the effects of thin film processing parameters on the mechanical properties of the thin films and their opto-mechanical effects on the optical response of fiber Bragg gratings (FBG).

Keywords: direct-write microfabrication, optical fiber devices, laser sintering of nano-particles

1 INTRODUCTION

In recent decades, various types of photonic devices have been developed to meet the ever-increasing demands in photonic sensing and communication industries. Optical fiber sensors, such as fiber Bragg gratings (FBG), are a subcategory of photonic devices widely utilized for structural, chemical, and biomedical sensing and also communication applications. The improvement of the functionality of optical fiber devices has always been a research topic. In this regard, coating of optical fibers with metal thin films has been considered as an effective approach. Previous research has shown that on-fiber metal thin films facilitates embedding of FBG sensors in metals [1], enables multiparameter measurements [2], and allows the fabrication of tunable optical filters [3]. We report the deployment of a laser-based direct printing method for pattering of FBGs with metal thin films to enhance their functionality. While physical vapor deposition methods can be utilized for on-fiber thin film coating, the patterning of fibers requires a rigorous process incorporating masks and additional hardware which makes the deposition process slow and expensive. In contrast, the drop-on-demand and layer-by-layer deposition features of the direct printing methods enable patterning of fibers with customized thicknesses.

2 ON-FIBER THIN FILM FABRICATION

Using our patented technology, we have established a manufacturing setup for customized pattering of metal thin films on optical fibers (Figure 1) [2]. The manufacturing process involves direct printing of nano-particles of metals, e.g., silver, followed by laser sintering. The on-fiber thin film deposition is performed by Laser-Assisted Maskless Microdeposition (LAMM) technology. The solution of nano-particles in an organic liquid, called nano-ink, is atomized to aerosol which is carried to a deposition nozzle with the help of a pneumatic system. The two-dimensional movement of the deposition nozzle relative to the optical fiber combined with the rotational motion of the fiber and the capability of the system in conformal deposition allow uniform on-fiber thin film patterning (Figure 2). This generates submicron thick and sub-30 µm wide tracks on the optical fiber, and wider coatings are generated by adjacent deposition of single tracks as shown in Figure 2. After the deposition of nano-particles, a laser beam is passed over the deposited layers to sinter the particles and make solid structures.

3 RESULTS AND DISCUSSION

The sintering of nano-particles is associated with atomic diffusion between particles which is controlled by the temperature increase generated by the laser radiation. The temperature is determined by the laser sintering parameters: laser average power, laser scanning speed, and laser spot size. The sintering of nano-sized particles is a complex process described by various atomic diffusion mechanisms: surface diffusion, grain boundary diffusion, and lattice diffusion. In sintering of nano-particles, the dominance of a diffusion mechanism depends on the particles size. In



Figure 1-The printing setup for the deposition of on-fiber silver thin films



Figure 2-Snapshots of a rotating optical fiber during the deposition of silver nanoink (The fiber rotates at 153 rpm.)

the early stages of the sintering process, surface diffusion and grain boundary diffusion with lower activation energies than lattice diffusion are dominant which result in the densification and neck-shape strucutre of the sintered particles. This phenomenon causes residual stress in the thin film and the optical fiber [4].

The sintered microstructure can be distinguished by the compact neck-shape structure of nano-particles (Figure 3). We have succeeded in depositing silver thin films with a thickness ranging from 500 nm to 10 μ m on optical fibers with 125 μ m diameter usgin the multi-layer deposition feature of the LAMM system (Figure 4). As Figure 4 shows, the drop-on-demand feature of the LAMM system enables customized patterning, e.g. periodic coating along the fiber.



Figure 3-Microstructure change in laser sintering of silver nano-particles (average particle size: <60 nm)

The functionality of the optical fiber devices depends on the mechanical properties of the thin films governing the opto-mechanical interaction between the films and the optical fiber. We have studied the effect of thin film processing parameters on the mechanical properties of the thin films. Our investigations have shown that the laser processing parameters have significant effects on the modulus of elasticity and hardness of the thin films (Figure 5).



Figure 4- Optical fiber coated with periodic silver thin films and the microstructure of the thin films

The on-fiber thin films can also affect the optical response of FBGs due to photo-elastic effect [1]. As shown in Figure 6, the single peak response of regular FBG is changed to an optical peak with sidebands upon the deposition of periodic on-fiber thin films. It is noteworthy to mention that the intensity of the sidebands can be controlled by the thickness of the deposited layers. Additionally, environmental factors such as temeprature



Figure 5-Effect of laser power on the mechanical properties of silver thin films

and axial strain can affect the sideband intensities. These features have numerous applications in optical fiber sensing [1].

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Figure 6-Optical reflection spectrum of a fiber Bragg grating after the deposition of periodic on-fiber thin films