Mechatronics 34 (2016) 137–146

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Fabrication and characterization of Bragg gratings in perfluorinated polymer optical fibers and their embedding in composites

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ARTICLE INFO

Article history:
Received 15 October 2014
Revised 25 September 2015
Accepted 14 October 2015
Available online 28 February 2016

Keywords:
Bragg grating fabrication
FBG
Perfluorinated polymer optical fiber
POF
CYTOP
SHM

ABSTRACT

Fiber Bragg gratings (FBG) have attracted interest especially in the field of structural health monitoring (SHM) and online process monitoring. The main objectives of this study are an ultraviolet laser based generation of Bragg gratings in a perfluorinated polymer optical fiber (POF) and their optical, thermo-mechanical and mechanical characterization. This kind of polymer fiber has a higher optical transparency than typical polymer fibers based on polymers with carbon hydrogen bonds like polymethylmethacrylate, which is the most used material for polymer optical fibers to date. Until recently only gratings inscribed by the phase mask technique in thin slabs of the amorphous fluoropolymer CYTOP (cyclic transparent optical polymer) made from polymer fibers were successfully detected. Here infrared spectra of Bragg gratings in the core of perfluorinated polymer optical fibers are presented and the embedding of the bare perfluorinated polymer fibers without the over-cladding (reinforcement) layer are described for the first time. The inscription of the gratings in the core of the polymer optical fiber was done using a krypton fluoride excimer laser (248 nm, 5 eV) and the well-known phase mask method. An advantageous mechanical characteristic of the perfluorinated polymer optical fibers compared to glass optical fibers is the failure strain. In structural health monitoring applications, where strains higher than 10% have to be measured, polymer optical fibers are feasible in contrast to glass optical fibers. The results are also promising regarding stability and reliability. This could open a new field of POF sensing of parts, structures and devices.

1. Introduction

Due to the increasing demand for fiber composite materials that continuously replace steel as the classical construction material in many areas, the interest and the demand for cost-efficient, embeddable sensors for structural health monitoring of composite structures have risen sharply. In particular, the use of structural health monitoring (SHM) techniques will enhance the prediction of structural failures, for example in buildings, pipelines and transportation structures. In these applications it is essential to integrate durable, reliable and small sensors which do not weaken the structure. A great potential is therefore seen in optical fibers which are already used in many applications [1].

Optical fiber sensors have several advantages compared to electrical sensors in many cases [1]. Among other things, the low attenuation loss and high data rates, combined with the low weight, the insensitivity to electromagnetic fields and the ability of multiplexing many sensors in a single fiber are great benefits. Optical fibers also provide the ability to measure various physical properties such as strains and temperatures.

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http://dx.doi.org/10.1016/j.mechatronics.2015.10.005
0957-4158/

Glass optical fibers (GOF) and polymeric optical fibers, both are of interest because of their specific characteristics for various applications. GOF are suitable for higher temperatures in comparison to POF. Pristine silica fiber typically has a failure strain of between 5% and 10% [2]. However, POF can tolerate more than 10% strain because of the material properties (e.g. ductility, Young's modulus) of amorphous polymers used for POF [3]. Because of this, POF could be better suited than GOF for monitoring structures like textiles that are themselves rather compliant [2]. It should be noted that polymers are viscoelastic materials and not necessarily more elastic than silica.

By the development of polymer fibers with low optical loss and high transmittance in the infrared (IR) spectral range which is used in telecommunication, they became interesting for technical applications in recent years. In 1985 the transparent, amorphous perfluorinated polymer CYTOP (cyclic transparent optical polymer) was introduced by Asahi Glass [4]. Since 2000 perfluorinated polymer optical fibers based on CYTOP are commercially available, initially sold under the brand Lucina by Asahi Glass [5]. Since then there are many opportunities for the use of CYTOP-based fibers in sensor technology applications, such as the structure condition monitoring – the structural health monitoring of load-bearing structural elements.

Fiber Bragg gratings (FBG) are prominent sensors in the field of SHM. Today's commercially available FBG sensors are based on glass optical fibers (GOF) although already in 1999 a polymer optical fiber Bragg grating (POFBG) was presented by Peng et al. [6]. Since then the generation of gratings in various kinds of POF was reported frequently. However, up to now, all of the polymer optical fibers used for successful Bragg grating fabrication were made of polymers that contain carbon hydrogen (C—H) bonds, with two exceptions [7,8]. They have therefore the disadvantage of quite high loss in the IR spectral range due to the absorption of C—H bonds and the relatively high water absorption in comparison to amorphous perfluorinated polymers.

At the 2nd International Conference on System-Integrated Intelligence reflection and transmission spectra of Bragg gratings inscribed with the phase mask method into the core of CYTOP-based fibers were presented to the scientific community for the first time [7]. This new kind of polymer optical FBG could be the first step for new types of sensors based on amorphous perfluorinated polymer optical fibers. In [8] the same kind of optical polymer fiber was used as in this work and in [7]. The Bragg grating inscription in [8] was done using a femtosecond laser.

In this publication the results of the fabrication and characterization of Bragg gratings in perfluorinated polymer optical fibers which were published in the conference proceedings paper [7] are presented in an extended version, including additional data and findings, of the conference proceedings paper. The additions are the results of the investigations of the mechanical, thermo-mechanical and thermo-optical characteristics of CYTOP-based fibers and FBG. Also a method for the local removal of the standard reinforcement layer of the perfluorinated GigaPOF bare fiber manufactured by Chromis Fiberoptics, Inc. is presented in order to get POF pigtails and patch cords for embedding in a composite plate with an effective embedding fiber diameter of 90 μm [7].

So far all of the POF integrated in composites have higher diameters than 90 μm which disturb the structural integrity of the composite more. Takeda [9] and also Kuang et al. [10] used POF with a diameter of 1000 μm for their investigations. Schukar et al. have laminated PMMA based optical fibers from Mitsubishi Rayon type ESKA GK40 into glass-fiber reinforced plastics with epoxy matrix. The POF were aligned in parallel to the reinforcing fibers so that the composite glass fibers were not bent by the POF with its comparatively large diameter. There were POF embedded with diameters of 1000 μm, 500 μm and 250 μm [11].

For the first time Hamouda has integrated CYTOP-based fibers with their standard over-cladding layer also in glass fiber reinforced plastics based on three-dimensional (3D) tissues [12]. CYTOP-based bare fibers with over-cladding layer have a diameter of 490 μm and 750 μm. The embedded fibers were characterized by transmission measurements and optical time domain reflectometry (OTDR) measurements. It was also found that an epoxy matrix causes lower optical losses than a vinyl matrix [12]. In this paper finally, the successful embedding of bare CYTOP-based fibers without their reinforcement layer into composites are presented for the first time.

2. Polymer fiber

2.1. Materials

Three kinds of graded-index perfluorinated POF with the item name GigaPOF bare fiber manufactured by Chromis Fiberoptics, Inc. were used in this work. All bare fibers have an over-cladding diameter of (490 ± 5) μm. This additional polyester and polycarbonate over-cladding protects the fiber [8]. Polyester and polycarbonate are not transparent in the deep ultraviolet. The bare fiber GigaPOF-50SR has a core diameter of (50 ± 5) μm, the bare fiber GigaPOF-62SR has a core diameter of (62.5 ± 5) μm and the bare fiber GigaPOF-120SR has a core diameter of (120 ± 10) μm. The core is surrounded by a cladding layer with a thickness in the range of around 10 μm to 20 μm. The core and cladding material used in these plastic fibers is a perfluorinated polymer and the core is doped with a perfluorinated molecule that has low volatility and is stable at elevated temperatures [13]. Fig. 1 shows a cross-section of such an extruded perfluorinated graded-index POF with the over-cladding layer.

If a wavelength of 248 nm is used for inscribing Bragg gratings in the doped core of the CYTOP POF the over-cladding has to be removed because the over-cladding material is not transparent at the wavelength of 248 nm. In [8] an inscribing wavelength of 517 nm was used and the over-cladding was not removed.

2.2. Preparation

The preparation procedure used in this work for the Bragg grating inscription consists of the following steps: The GigaPOF-50SR sample was cut of approximately 30 cm of length by a razor blade. For the Bragg grating inscription the over-cladding layer was removed by chemical etching with a manual method as follows. One end of the POF sample was dipped with a length of approxi-

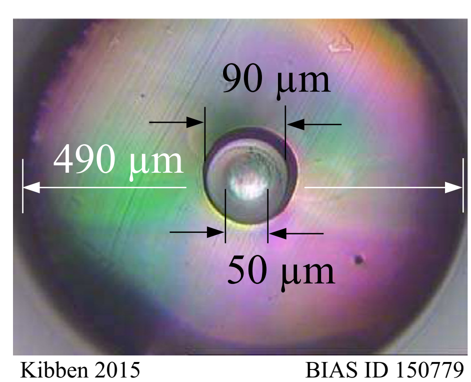

Fig. 1. Cross-section of extruded perfluorinated graded-index POF with an over-cladding (reinforcement) layer generated by a razor blade cut; core/cladding/over-cladding, 50 μm/ 90 μm/ 490 μm; the photograph was taken with the Interphako microscope.