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1-m tunable optical delay line using microfluid sliding in a hollow-core fiber: Feasibility study

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ABSTRACT

A novel variable optical delay line based on a hollow-core photonic bandgap fiber is proposed. The device incorporates microfluid, the end surface of which serves as an optical reflector, in the hollow-core of the fiber. The position of the fluid end is controlled by a syringe pump to change the optical delay of the reflected beam. We demonstrate wide tunability of the optical delay up to 1 m with a scan speed of several mm/s. The return loss and beat pattern in the reflected signal is studied and the potential of the device as an ultra-long delay line is discussed.

1. Introduction

Variable optical delay lines are widely used in interferometers, such as low coherence interferometers, stellar interferometers, and Fourier transform spectroscopy, where a series of optical output is collected while changing the optical path length of one beam before combining it with another. Other applications of optical delay lines include polarization mode dispersion compensators and optical buffers, where optical pulses are delayed intentionally by the time required for synchronization. The maximum delay length, tuning speed, linearity of the delay, wavelength/polarization dependence, insertion loss, and compactness are important characteristics to be considered, of which some becomes more critical depending on the applications.

Various techniques have been proposed to achieve a fast and widely tunable optical delay. A rotating or vibrating mirror [1,2] has been used to change the geometrical path of the beam. All-fiber compact delay lines with low insertion loss have been demonstrated using a pair of chirped fiber bragg gratings [3] under tunable strain or stimulated Brillouin scattering [4]. The all-fiber configuration of the devices facilitates a compact and low-loss system, whereas the grating-based devices suffer from narrow bandwidth of the operating wavelength. A time-prism pair was implemented to achieve a high speed scan rate using a pair of optical frequency shifters and a highly dispersive medium [5]. However, its application was limited to optical input in pulses.

The primitive form of variable optical delay comprises a collimation lens and a reflective mirror moving along the optical axis. Typically, a variable delay of several centimeters is possible with a scan speed of a few mm/s. Since the system requires delicate optical alignment and it has a low mechanical stability, its applications are limited.

In this paper, we propose a novel optical delay line in all-fiber form. It incorporates a movable reflective mirror, similar to the primitive configuration. However, the mirror slides inside the optical fiber instead of in free space. Light propagates along the hollow core of the photonic bandgap fiber and is reflected on the surface of the fluid (mirror) in the hollow core. A change in optical delay is achieved through infusion and withdrawal of the fluid using a syringe pump. This scheme allows several important benefits. Since the optical reflector moves along the hollow core of the fiber, there is no need for optical alignment. Because optical loss does not increase with the delay length, except for the propagation loss of the fiber, the delay length can be greatly extended provided fluid control is possible. The optical path does not need to be straight; the whole length of fiber can be coiled within a diameter of several centimeters to make the device compact. In this study, we implemented this idea experimentally to examine its feasibility as an optical delay line with an ultra-long delay length.

2. Experimental setup

The experiment setup is shown in Fig. 1(a). In our study, we used the hollow-core photonic bandgap fiber (HC-PBF) of HC19-1550-01 that has a hollow core with a diameter of 20 μm, and provides optical guidance at the 1.55 μm wavelength band [6]. A 1 m-long HC-PBF was connected to a single-mode fiber by butt-coupling. The other end of the HC-PBF was arc-spliced to a capillary tube with a hole diameter of 20 μm, and then

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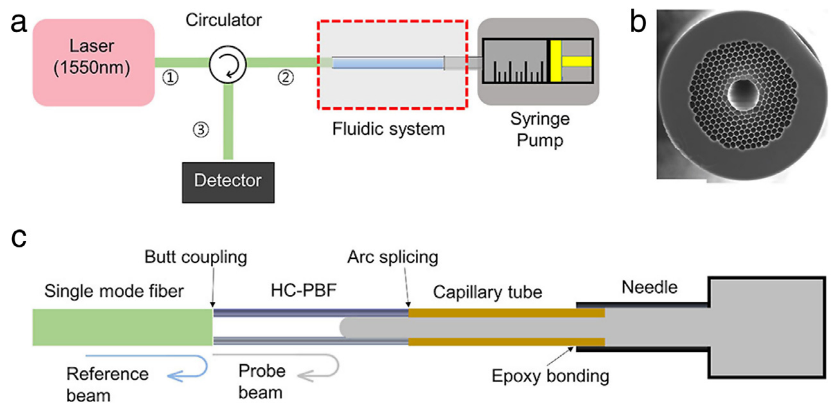

Fig. 1. (a) Experimental setup, (b) cross-section of the hollow-core photonic bandgap fiber, and (c) schematic of the optical fiber-capillary-syringe pump connection.

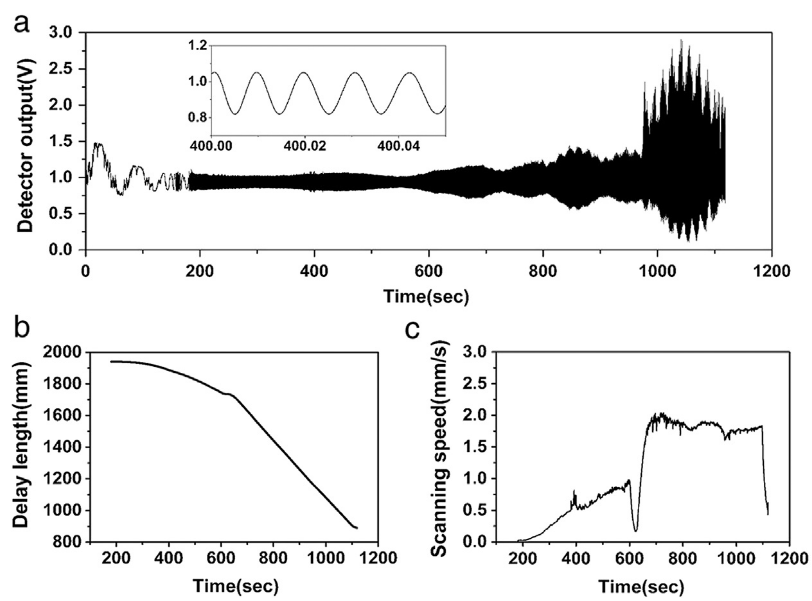

Fig. 2. (a) Optical interference signal obtained while injecting liquid in hollow-core fiber, (b) delay length change obtained by counting number of oscillations of (a), and (c) scanning speed of delay or time derivative of (b).

the capillary tube was epoxy-bonded to the metal needle of the syringe to ensure a hermetic seal. The position of the fluid end was controlled by a syringe pump (Harvard Bioscience Co. PY2 70-2209). The optical delay is determined by the roundtrip path of the optical signal reflected at the mercury end. In our study, mercury was selected as the fluid because of its low viscosity and high reflectivity [7], which are good for fast flow and low optical loss, respectively. A distributed-feedback (DFB) laser with a wavelength of 1550 nm was input through the single mode fiber to track the change in the optical delay. The laser light was divided into two light beams after propagating through the circulator from Port 1 to Port 2. One of the light beams was reflected at the end of the single-mode fiber by Fresnel reflection [8], and the other was reflected at the end of mercury after propagating in the HC-PBF. The interference signal of the two beams was detected at Port 3. While the fluid flows, the detector output fluctuates as shown in the inset of Fig. 2(a), and thus we could monitor the change in the optical path length [9].

3. Control of optical delay

Fig. 2(a) shows the measured detector output as a function of time. At 0 s, the syringe pump was turned on and started injecting mercury into the HC-PCF at a rate of 20 nl/min and the detector output of the interference signal started to fluctuate. The insets show the sinusoidal signal in detail, where one cycle of the sinusoidal fluctuation

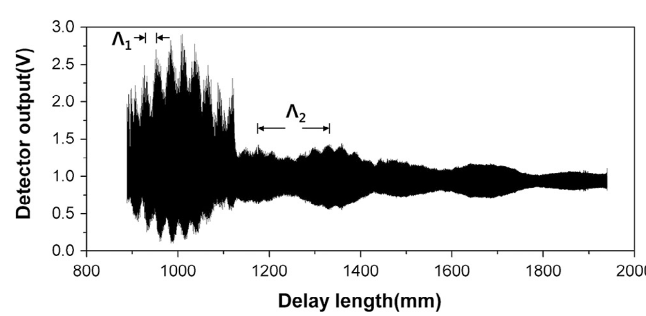

Fig. 3. Optical interference signal vs. delay length converted from Fig. 2(a) using delay-time relation of Fig. 2(b). It contains dual beating periods, $\Lambda1$ and $\Lambda2$.

corresponds to a fluid movement of $\lambda/2 = 775$ nm [9]. The shorter period of the signal at $T = 800$ s compared to that at $T = 500$ s indicates faster movement of the fluid.

By fringe counting the oscillating signal using a computer program, we could obtain information regarding the position of the fluid end, as shown in Fig. 2(b). Fig. 2(c) shows the speed of the fluid, which is the time derivative of the position in Fig. 2(b). The speed of the mercury end increased gradually after the pump started and became