All-fiber power sensor based on silicon-germanium core fiber F-P cavity

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Abstract. An all-optical power sensor based on silicon-germanium (SiGe) core fiber Fabry-Perot (F-P) cavity is proposed. The F-P sensor was formed by fusion splicing SiGe core fiber with conventional single-mode fiber (SMF). The 980 nm laser can be absorbed efficiently by the silicon-germanium material, resulting in the temperature increase inside the cavity, which induces the drifts of the reflection spectrum. The injected power has a very good linear relationship with the drifts experimentally, and the power sensitivity is up to 1.7 nm/mW, which may have great potential for all-fiber power detector.

1. Introduction
Recently, due to the excellent material advantage of semiconductor core fiber, its development has been widely concerned. Especially semiconductor core fiber takes advantages of high nonlinearity characteristics, high Raman gain and medium-infrared transparency in optical properties [1-2], so its presence has already given optical fiber new features and enormous possibilities for fiber-based devices and sensors. Since J. Ballato, et al. firstly proposed molten core method to prepare silicon core fiber in 2008 [3], the research on semiconductor core fiber has got rapid development. Various kinds of semiconductor core fiber have been prepared, such as germanium core fiber, zinc-selenide core fiber and so on [4-5]. Further characteristic exploration of semiconductor core fiber provides the basis for the realization of all-optical device. For example, silicon core fiber (SCF) has a thermo-optic coefficient (TOC) approximately 10 times larger than that of fused silica, resulting in higher temperature sensitivity [6]. And the large thermal diffusivity of the SCF leads to high response speed, which is more than 60 times larger than that of fused silica [7]. Especially, SiGe alloy has the greater TOC compared with silicon. Thus, SiGe core fiber can potentially provide better performance for optical fiber sensing technology. Currently, most of cavity medium of F-P sensing devices is either silica or air, the temperature sensitivity of fiber FPI is only 14 pm/℃ owing to the limitation of fiber sensor materials [8]. Such a low sensitivity cannot meet the actual requirements in some special cases. Therefore, the SiGe core fiber has been introduced to improve the performance of sensor.

In this paper, we present an all-fiber optical power sensor based on the silicon-germanium core F-P cavity, and demonstrate its power sensitivity is up to 1.7 nm/mW when 980 nm laser irradiating on the SiGe core cavity.
2. Principle
The schematic diagram of SiGe core F-P sensor is shown in Fig. 1. The silicon-germanium material of F-P cavity has a strong absorption between 500 nm and 1000 nm and could transform it into internal energy high efficiently inside the cavity [9]. This photothermal effect causes temperature distribution on F-P cavity, which leads to interference spectrum variation. In this scheme of Fig. 1, 980 nm laser is injected into the SiGe core formed F-P cavity. Meanwhile, broadband light with the central wavelength of 1550 nm is also guided into the cavity to monitor reflection spectrum variation, in order to characterize its response to the injected laser power. Different injected laser power corresponds to varying degrees of interference wavelength drift.

![Fig. 1. The schematic diagram of SiGe core fiber F-P cavity.](image)

According to the principle of temperature sensing of F-P cavity, the resonant cavity length and the refractive index of the cavity will change with the temperature inside the cavity. The optical path difference between the two reflection beams will also change, resulting in changes in the phase difference between the interference light beams. From the reflection spectrum, we can intuitively observe the drift of interference wavelength. For fiber F-P cavity with cavity length of L and dielectric refractive index of n, the relationship of the two parameters and the temperature change can be expressed [8]:

\[ \Delta L = L \cdot \alpha \cdot \Delta T, \quad \Delta n = n \cdot \varepsilon \cdot \Delta T, \]

where \( \Delta L \) is the cavity length change, \( \alpha \) is the thermal expansion coefficient of the medium, \( \Delta n \) is the index change, \( \varepsilon \) is the thermo-optical coefficient of the medium, and \( \Delta T \) is temperature change. As can be seen from the above equations, the phase difference of F-P cavity is proportional to the temperature, and it is mainly determined by the thermo-optical coefficient and the thermal expansion coefficient of the cavity medium. In order to improve the sensing resolution of fiber-optic F-P cavity, the SiGe core material with greater thermal expansion coefficient and thermo-optical coefficient is considered.

3. Fabrication and experiments
The SiGe core fiber employed in this experiment was fabricated with rod-in-tube method with homemade fiber draw tower of our laboratory. Before the drawing process of SiGe core fiber, we mixed the germanium powder and the silicon powder in a specific ratio, then put the mixed powder into the silica tube. One end of the silica tube was collapsed beforehand to form the fiber preform. Through the melt and drawing process in the graphite furnace, we prepared the SiGe core fiber with a perfect circle core and a clean core-cladding interface. Then, to form F-P cavity inside the SiGe core fiber, the homemade SiGe core fiber was manually spliced with the conventional single mode fiber (SMF) with a commercial arc splicer. Since the melting points of the two fibers are different during the splicing process, we could introduce certain thermal gradient into the fiber core by tuning the splicing parameters such as interval, stepping rate and location aligning the electrode axis, then the SiGe core F-P cavity was formed close to the splice point.

In order to verify that the cavity medium is a silicon-germanium material, we used a confocal Raman spectrometer to measure the Raman spectrum of the fiber core. The result is shown in Fig. 2. We can find clearly the Raman vibrational peaks of 289.2 cm\(^{-1}\), 406.8 cm\(^{-1}\) and 484.9 cm\(^{-1}\), which
correspond to the optical phonon modes of Ge-Ge, Si-Ge and Si-Si respectively. And the SiGe alloy is confirmed in the cavity. The strain in the silicon-germanium core causes the peak shifts of the three vibrational modes, and the vibration peak position is related to the proportion of the material in the alloy.

![Graph showing Raman spectrum of SiGe core material of F-P cavity.](image)

**Fig. 2.** Raman spectrum of SiGe core material of F-P cavity.

After that, to characterize the 980 nm laser power detecting property of the SiGe core F-P sensor, the experimental setup was built according to the schematic diagram of Fig. 3a. The incident light from 1550 nm broadband light source was propagated through the input port (port 1) of the fiber optic circulator (OC), one of the output (port 2) was connected with the 1550 nm input port of the 980/1550 nm wavelength division multiplexer (WDM), and the backward reflection was collected to the optical spectrum analyzer (OSA) through the port 3 of the OC, recording the F-P’s reflection spectrum. The 980 nm laser was delivered to heat the SiGe core through the other input port of the WDM. The reflection spectrum of F-P was affected by the thermal effect induced by the laser injection. Then, we can evaluate the performance of the sensor through the resonance wavelength shift by altering the injected laser power. The inset Fig. 3b privates the microscope image of the formed F-P cavity after fusion splices of the SiGe core fiber and the SMF.

![Experimental setup for laser power detecting](image)

**Fig. 3.** Experimental setup for laser power detecting

4. Result and discussion
To characterize the laser power sensing property of SiGe core fiber F-P cavity, the optical power of 980 nm laser was successively increased from 0 mW to 6 mW. As illustrated in Fig. 4, the reflection spectrum shifts to longer wavelength regularly when the laser power increases (Fig. 4a), and vice versa (Fig. 4b).
Fig. 4. Reflection spectra with respect to the injection optical power of 980 nm laser: (a) optical power increases; (b) optical power decreases.

In order to quantitatively observe the drift at different injection power, Fig. 5 gives the resonant peak wavelength of 1415.1 nm shifting with the applied 980 nm laser power. We could see that the optical power response curves are nearly linear, and the 980 nm optical power sensitivity of the F-P cavity is about 1.7 nm/mW.

Fig. 5. Linear fitting of laser power to the reflection wavelengths of 1415.1 nm, where the black line is fitting as power increases, and the red line is fitting as power decreases.

Such phenomena support the analysis that high absorption of silicon-germanium core to the laser power leads to high temperature on the cavity, which induces the variation of F-P’s cavity length, thus the F-P’s reflection spectrum changes. The reflectance spectra coincide before and after laser irradiation, which proves the good stability of SiGe core fiber F-P sensor.

5. Conclusion
In conclusion, an all-fiber power sensor based on the SiGe core fiber F-P cavity was proposed and demonstrated. Firstly, SiGe core fiber F-P cavity could be prepared by splicing the homemade SiGe core fiber with the SMF. Then the presence of SiGe core material was confirmed by Raman spectroscopy. After that, based on the strong absorption of silicon-germanium core from the visible to the near IR wavelength range, we experimentally characterized the response of reflection spectrum on the injected 980 nm optical power change. Good linearity exists between the detecting power and the resonant wavelength. The optical power sensitivity is up to 1.7 nm/mW. This kind of SiGe core fiber F-P cavity may have great potential for in-fiber optical power detector.
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