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Measurement of Er$^{3+}$-doped concentration in optical fiber by using fiber Bragg grating Fabry–Perot cavity ring-down spectrum

Haiyan Chen (陈海燕)$^{1*}$, Lilin Chen (陈礼林)$^{1}$, Cong Chen (陈聪)$^{1}$, Meng Wang (王蒙)$^{1}$, Qi Li (李聪)$^{1}$, and Kaiqiang Huang (黄凯强)$^{2}$

$^{1}$School of Physics Science and Technology, Yangtze University, Jingzhou 434023, China
$^{2}$School of Electronics & Information, Yangtze University, Jingzhou 434023, China

*Corresponding author: hychen@yangtzeu.edu.cn

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We propose and experimentally demonstrate a novel approach to measure the Er$^{3+}$ concentration in Er$^{3+}$-doped silica fiber by fiber Bragg grating Fabry–Perot (FBG-FP) cavity ring-down spectrum. The relation between the cavity ring-down time and the Er$^{3+}$-doped concentration is derived. The results demonstrate that the cavity ring-down time is a function of the temperature of FBG, and an Er$^{3+}$-doped concentration of $0.03 \times 10^{20}$ m$^{-3}$ at the FBG operation temperature of $25^\circ$C is obtained, which is consistent with the commercial Er$^{3+}$-doped silica fiber parameter. The results obtained have theoretical guidance and develop a new method to measure the ion doped concentration in solid matter.

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Cavity ring-down spectroscopy (CRDS) has been attracting some attention due to its applications in molecular spectroscopy, military, petrochemical, transportation, building and structural monitoring, chemical, and biomedical sectors$^{[3–5]}$. There are some kinds of cavity structures such as traditional resonant cavity composed of two high-reflectivity mirrors, fiber Fabry–Perot interference$^{[6]}$, fiber Bragg gratings$^{[7]}$, and a fiber loop$^{[8]}$. In our previous work, we reported some researches on single-mode fiber CRDS for photonic generation of microwave and millimeter waves and pressure sensing$^{[9–11]}$. In this paper, we measure the Er$^{3+}$ concentration in Er$^{3+}$-doped fiber by Fiber Bragg Grating Fabry–Perot (FBG–FP) cavity ring-down spectrum, the effect of the operation temperature of FBG on the cavity ring-down time is discussed.

The schematic diagram of experimental setup is shown in Fig. 1, which consists of a 1550-nm DFB (Opwit CA9005 DFB-EML) laser modulated by 25-KHz RF (Opwit Laser CA8004 System) signal, and the modulated signal is injected into the FBG-FP cavity, including absorption and the fiber couplers’ insertion losses. The time required for the light intensity to decrease to $1/e$ of the incident light intensity observed by the detector is referred to as a ring-down time, $\tau_0$, and is given by

$$\tau_0 = \frac{nL}{cA}, \quad (2)$$

When a segment of Er$^{3+}$-doped active fiber is inserted into the passive FBG-FP cavity, an Er$^{3+}$ absorption-induced loss occurs. Assuming that the refractive index of the active fiber is equal to that of the passive fiber, the introduction of this Er$^{3+}$ absorption-induced loss, $B$, causes a change in the ring-down time, $\tau$:

$$\tau = \frac{n(L + l)}{c(A + B)}, \quad (3)$$

where $B = \alpha_{3p}l$, $\alpha_{3p}$ is the absorption loss coefficient of Er$^{3+}$ in units of, e.g., m$^{-1}$, and $l$ is the length of Er$^{3+}$-doped fiber.

From Eqs. (2) and (3), we have

$$\alpha_{3p} = \frac{1}{cLn} \left( \frac{n(L + l)}{\tau - \frac{nL}{\tau_0}} \right) \quad (4)$$
The Er$^{3+}$ doped can be written as\cite{13}

$$\rho = \frac{|\alpha_{fe}|}{\sigma(10 \log_{10}(e))},$$

where $e = 2.71828$, $\rho$ is the Er$^{3+}$-doped concentration, $\sigma$ is the absorption cross section, which usually is $5.36 \times 10^{-25}$ m$^2$ for Er$^{3+}$-doped silica fiber at room temperature.

In the experiment, the lengths of passive FBG-FP cavity and Er$^{3+}$-doped fiber are 1 m and 0.201 m. The typical output spectrum of FBG-FP cavity is shown in Fig. 2. It manifests a time-dependent intensity decay of light leaking from a FBG-FP cavity with pulsed laser injection, and the decay shows an exponential behavior, and its decay time called cavity ring down time is a function of intra-loss.

When the operation temperature of FBG is 25 °C, the output spectra of passive and active FBG-FP cavity are plotted in Figs. 3 and 4, respectively. From these figures, we can obtain $\tau_0 = 3.6 \mu$s, $\tau = 7.8 \mu$s, and the absorption coefficient of Er$^{3+}$-doped fiber is $-6.2$ m$^{-1}$, the Er$^{3+}$-doped concentration is $0.3 \times 10^{25}$ m$^{-3}$, which consists with the commercial Er$^{3+}$-doped fiber parameter.

![Fig. 2. Typical out spectrum of FBG FP cavity.](image1)

![Fig. 3. Out spectrum of passive FBG FP cavity at 25 °C.](image2)

![Fig. 4. Out spectrum of active FBG FP cavity at 25 °C.](image3)

We also discuss the effect of the temperature of FBG on the cavity ring-down time, which is shown in Fig. 5. The point and asterisks are the measured data for passive and active FBG-FP cavity, respectively. The solid and broken lines are the fitting curves. The cavity ring-down time is a function of the operation temperature of FBG. When the temperature changes from 5 °C to 30 °C, the cavity ring-down time changes 1 μs for passive FBG-FP. In order to detect the little change, more accurate detectors and oscilloscopes are demanded. The cavity ring-down time grows with the increase of the temperature of the FBG. The effect of the absorption loss of the doped fiber in the cavity on the cavity ring-down time is of importance.

In conclusion, we propose and demonstrate a novel measurement approach for Er$^{3+}$ concentration in Er$^{3+}$-doped fiber by FBG-FP cavity ring-down spectrum. The present work gives demonstration of developing a new solid doped ion concentration measurement approach.

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