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

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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 relationship 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 0.3×10^{25} m^{-3} at the FBG operation temperature of 25 °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[1–5]. 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-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; the temperature controller is Opwit Laser CA8004 System, and the signal passing thought the FBG-FP cavity with two identical FBGs as cavity mirrors is detected by a photo detector (PD, Thorlabs DET01CFC), and the ring-down

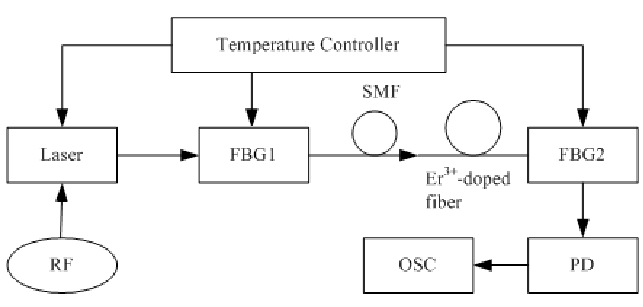

Fig. 1. Schematic diagram of experimental setup

spectrum is measured by an oscilloscope (OSC, Tektronix TDS2022B), and also the two identical FBGs are collected by a piece of single-mode fiber (SMF-28) and a piece of Er^{3+} doped fiber (Er110-4/125, nLIGHT Corporation).

The output intensity of the FBG-FP cavity can be written as[12]

$$I(t) = I_0 \exp\left(-\frac{cAt}{nL}\right), \tag{1}$$

where I_0 is the initial input intensity, L is the fiber length, c is the speed of light in vacuum, $n(\approx 1.5)$ is the refractive index of the fiber, and A is the total loss in each round trip for passive cavity, including absorption loss 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, τ_0, and is given by

$$\tau_0 = \frac{nL}{cA}. \tag{2}$$

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, τ:

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

where $B = \alpha_{Er} l$, α_{Er} 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

$$\alpha_{Er} = \frac{1}{cl}\left(\frac{n(L+l)}{\tau} - \frac{nL}{\tau_0}\right). \tag{4}$$

The Er^{3+} doped can be written as[13]

$$\rho = \frac{|\alpha_{Er}|}{\sigma(10\log_{10}(e))}, \tag{5}$$

where $e = 2.71828$, ρ is the Er^{3+}-doped concentration, σ is the absorption cross section, which usually is 5.36×10^{-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 ℃, the output spectra of passive and active FBG-FP cavity are plotted in Figs. 3 and 4, respectively. From these figures, we can obtain τ_0 = 3.6 μs, τ = 7.8 μs, and the absorption coefficient of Er^{3+}-doped fiber is –6.2 m^{-1}, the Er^{3+}-doped concentration is 0.3×10^{25} m^{-3}, which consists with the commercial Er^{3+}-doped fiber parameter.

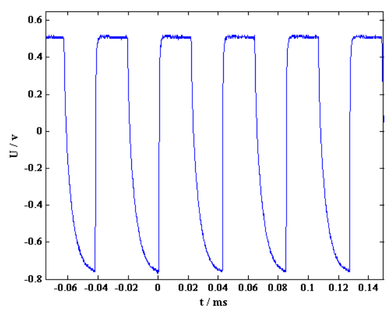

Fig. 2. Typical out spectrum of FBG FP cavity.

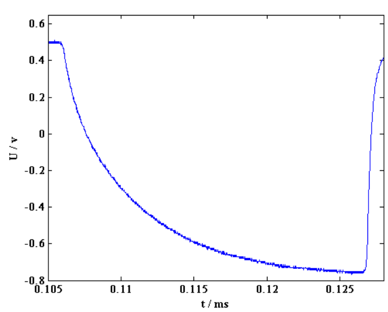

Fig. 3. Out spectrum of passive FBG FP cavity at 25 ℃.

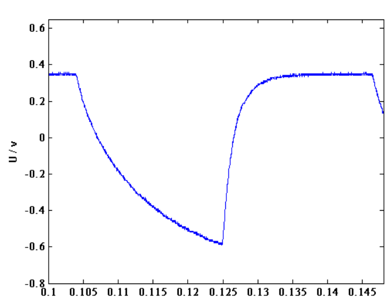

Fig. 4. Out spectrum of active FBG FP cavity at 25 ℃.

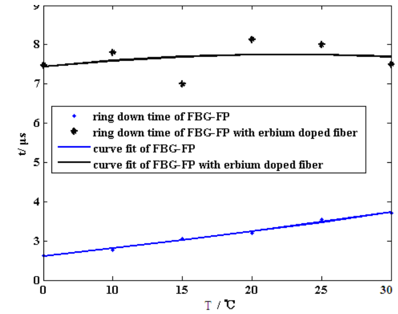

Fig. 5. Ring down time as a function of the temperature of FBG.

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 ℃ to 30 ℃, 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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