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 using 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 $0.3 \times 10^{16}$ 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-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 through the FBG-FP cavity with two identical FBGs as cavity mirrors is detected by a photo detector (PD, Thorlabs DET01CFC), and the ring-down 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

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

(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, $\tau_0$, and is given by

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

(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, $\tau$.

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

(3)

where $B = \alpha_{Er} l$, $\alpha_{Er}$ 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

$$\alpha_{Er} = \frac{1}{cl} \left(\frac{nL}{\tau} - \frac{nL}{\tau_0}\right).$$

(4)
The Er\textsuperscript{3+} doped can be written as\cite{13}

\[ \rho = \frac{|\alpha|}{\sigma(10\log_{10}(e))}, \]

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

In the experiment, the lengths of passive FBG-FP cavity and Er\textsuperscript{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 \( \tau = 3.6 \mu s \), \( \tau = 7.8 \mu s \), and the absorption coefficient of Er\textsuperscript{3+}-doped fiber is \(-6.2 \text{ m}^{-1}\), the Er\textsuperscript{3+}-doped concentration is \( 0.3 \times 10^{25} \text{ m}^{-3} \), which consists with the commercial Er\textsuperscript{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\textsuperscript{3+} concentration in Er\textsuperscript{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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