# Raman Scattering Enhancement Characteristic of Hf-Doped Silica Fiber

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**Abstract** Stimulated Raman scattering is one of the most important problems in the field of nonlinear fiber optics. The Raman scattering enhancement characteristic of Hf-doped silica fiber and Hf/Al co-doped silica fiber are researched. The Raman spectra of Hf-doped silica fiber and Hf/Al co-doped silica fiber are measured by using 785 nm exciting light, and compared with conventional single-mode fiber (SMF). The experimental results show that Hafnium doping or Hafnium/Aluminum co-doping can enhance the optical fiber Raman scattering intensity, and achieve a good Raman scattering enhancement effect.

**Key words** nonlinear optics; Raman scattering; Raman spectrum; Hf-doped silica fiber; Hf/Al co-doped silica fiber

**OCIS codes** 190.2640; 290.5910; 300.6450; 160.6990

# 掺铪石英光纤的拉曼散射增强特性

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**摘要** 光纤中的受激拉曼散射是非线性光纤光学领域的重要研究课题之一。研究了掺铪石英光纤及铪铝共掺石英光纤的拉曼散射增强特性，采用 785 nm 的激发光测量了掺铪石英光纤及铪铝共掺石英光纤的拉曼光谱，并与常规单模光纤的拉曼光谱进行了对比。实验结果表明在光纤中掺杂铪元素或铪铝元素共掺能够明显地增强光纤的拉曼散射强度，并获得很好的拉曼散射增强效果。

**关键词** 非线性光学；拉曼散射；拉曼光谱；掺铪石英光纤；铪铝共掺石英光纤

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## 1 Introduction

Stimulated Raman scattering (SRS) is one of the important nonlinear effects in the optical fiber. Recently the Raman fiber laser and Raman fiber amplifier have attached much more attentions with their special characters[1-2]. The Raman scattering is extremely weak, and it is a cumulative process, the interaction time between the incident light and materials is very short, so it is difficult to accumulate the Raman scattering signal for the general material. While in the optical fiber, exciting light transmits in the optical fiber, and the interaction time between the fiber material and light wave is much longer. Raman scattering effect is more obvious, so the Raman spectrum of optical fiber can be observed more easily[3]. Nevertheless, the fiber Raman scattering signal in the fiber is still not strong enough for some applications of optical fiber Raman technology. At present, people have studied the Raman spectrum properties of plastic optical fiber, liquid-core optical fiber and multi-

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component glass fiber[4-7]. Compared with conventional fiber, Raman spectra of plastic optical fiber only has some differences in the Raman frequency shift, its Raman enhancement property remains to be further studied. Although the Raman scattering enhancement effect of liquid-core optical fiber is very obvious, because of its unique structure, which has some organic or inorganic solution in the core layer, it is difficult to be applied to long distance communication. Multi-component glass fiber is difficult to be applied to silica fiber for its chemical stability and mechanical strength limitation . Therefore, looking for a special silica fiber with enhanced Raman scattering effect is necessary.

In this paper, a new kind of Hafnium (Hf) doped special silica optical fiber was fabricated with the method of modified chemical vapor deposition (MCVD) and atomic layer deposition (ALD) technologies. Raman spectra of Hf-doped silica fiber and Hf/Al co-doped silica fiber were measured and compared with conventional single-mode optical fiber.

## 2 Fabrication

The $SiO_2$ layer was deposited on the inner-surface of pure silica tube with MCVD method. Then the silica tube was taken into the chamber of ALD and doped with $HfO_2$ to form the core layer[8-9]. In the process of the precursor deposition, the substrate temperature was around 220 ℃ ~350 ℃. The tube was collapsed to form the Hf-doped preform with MCVD by heating it up to 2000 ℃. The preform was drawn into the Hf-doped optical fiber. The Hf-doped fiber is a single-mode fiber with the index difference between the core and the cladding $\Delta n = 5.5 \times 10^{-3}$. The diameters of core and cladding are 7.78 μm and 126.12 μm, respectively.

For Hf/Al co-doped silica fiber, $HfO_2$ and $Al_2O_3$ were deposited in the silica tube alternatively with ALD technology. The Hf-doped film and Al-doped film were grown at 300 ℃. After ALD deposition, the Hf/Al co-doped silica preform was made, and then drawn into the Hf/Al co-doped special fiber with conventional fiber drawing tower. The Hf/Al co-doped fiber is also a single-mode fiber with the index difference between the core and the cladding $\Delta n = 7 \times 10^{-3}$. And the diameter of core and cladding are about 7.97 μm and 120.69 μm, respectively.

## 3 Experiments and Results

### 3.1 Raman spectrum of doped silica fiber

Raman spectra include Stokes lines and anti-Stokes lines. the Stokes line intensity is about several hundreds or even thousands times higher than the anti-Stokes line intensity, so Raman spectrum is measured on the basis of Stokes line. The quantitative characterization of molecular vibration spectrum can be presented by Raman spectrum peak position and intensity. The relationship between Raman shift and Raman wavelength is described by $\Delta v = 1/\lambda - 1/\lambda_0$, where $\lambda$ and $\lambda_0$ are the wavelength of scattered light and incident exciting light, respectively, and $\Delta v$ is Raman shift whose unit is $cm^{-1}$. Raman scattering intensity is the embodiment of Raman scattering cross section (RSCS) in Raman scattering spectrum measurement. It indicates the probability of particles within spatial angle scattered by the incident exciting photons. The larger RSCS is, the greater the proportion of the incident exciting light is scattered [10]. The following equation indicates their physical meanings and relationships [11]:

$$\sigma = \frac{P_{ro}}{P_{po}\Omega\Delta\omega}\frac{\alpha_r - \alpha_p}{1-\exp[-L(\alpha_r - \alpha_p)]}\frac{\int_{Acore} S(r)\mathrm{d}A}{\int_{Acore} S^2(r)\mathrm{d}A}, \tag{1}$$

where $P_{po}$ is the excitation light intensity, $P_{ro}$ is the Raman Stokes line intensity, $L$ is length of optical fiber where Raman spectrum be collected, $\Delta\omega$ is bandwidth of Raman spectrum peaks, $\Omega$ is the solid angle of Raman scattering, and $S(r)$ is the distribution function of the refractive index. $\alpha_r$, $\alpha_p$ are the fiber attenuations at the Raman wavelength and the pump wavelength, respectively. According to Eq.(1), Raman intensity of optical fiber is related with the length and refractive index of optical fiber. Doping different materials in optical fiber can change the optical fiber refractive index. In this paper, the Raman scattering enhancement characteristic of Hf-doped silica fiber is researched.

### 3.2 Raman spectrum measurement setup for Hf-doped special silica optical fiber

Hf-doped silica fiber Raman spectrum measurement setup is shown in Fig.1. This measurement system is mainly included laser source, objective, Raman spectrometer and computer. The exciting light is coupled into one end of Hf-doped special silica optical fiber by a 10× len. The other end of the fiber is immersed into glycerol. The Raman scattering signal is collected by a commercial confocal micro-Raman spectroscopy (Renishaw inVia plus) and the Raman spectroscopy is displayed on the computer. Hf-doped optical fiber has a strong absorption at 785 nm, which helps exciting nonlinear effect, and mean while avoiding the fluorescence interference by using 785 nm exciting light. According to the experimental measurement system, Raman spectra of different length optical fibers were obtained.

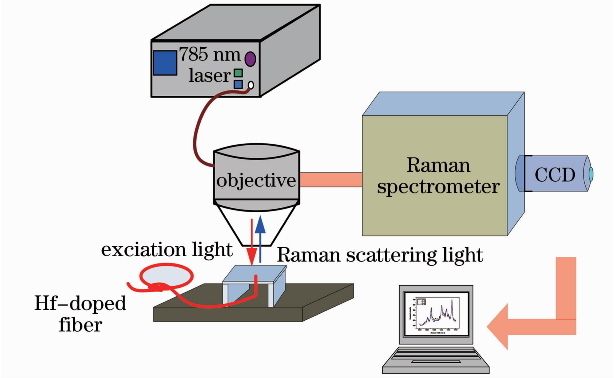


Fig. 1 Raman spectroscopy measurement setup

### 3.3 Raman spectra of Hf-doped silica optical fiber and conventional single-mode optical fiber

The shape of Raman spectra is independent of the wavelength of the exciting light, Raman scattering is extremely weak, the shorter the wavelength of exciting light is, the more easily excited fluorescence. In order to avoid fluorescence interference, 785 nm exciting light source was adopted in the measurement. The power of exciting light is 25 mW, the Raman spectra of conventional single-mode optical fiber and Hf-doped fiber are measured under the same test conditions with the length of 10 m. The measuring results are shown in Fig. 2. There are several obvious Raman spectrum peaks located at 440.5, 489.5, 601.2, 823.6, 1005.1, 1294.2, 1452.4, 1610.5, 1728.9, 2872.4, and 2931.9 $cm^{-1}$. Compared with the Raman spectrum of conventional single-mode silica fiber, their Raman spectrum peaks are almost in the same position. But the Raman scattering intensity of Hf-doped special silica optical fiber is much stronger than that of conventional single-mode optical fiber at these peaks. For 10 m length fiber, Raman peak intensity of Hf-doped special silica optical fiber is approximately 2.8 times more than that of conventional single-mode optical fiber at 440.5 $cm^{-1}$, 1.8 times at 823.6 $cm^{-1}$, 2.3 times at 1452.4 $cm^{-1}$, 1.9 times at 2872.4 $cm^{-1}$, and 3 times at 2931.9 $cm^{-1}$.

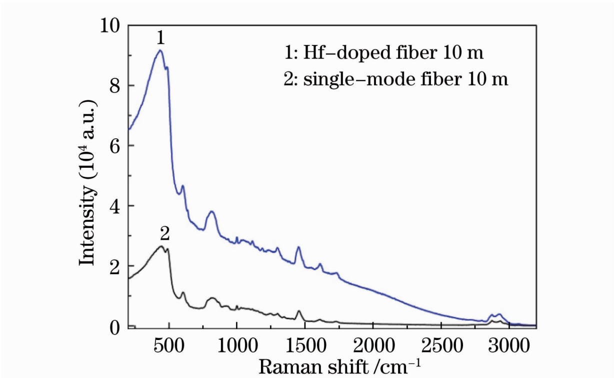


Fig. 2 Comparison between Raman spectra of Hf-doped silica fiber and conventional single-mode optical fiber

The experimental results indicate that Hf-doped special silica optical fiber can enhance the Raman scattering intensity in these bands.

### 3.4 Raman spectra of Hf/Al co-doped silica optical fiber and conventional single-mode optical fiber

The Raman spectrum of Hf/Al co-doped fiber is measured, and compared it with conventional single-mode fiber. As shown in Fig. 3, there are several obvious Raman spectrum peaks located at 440.5, 490.6, 603.2, 823.6, 1005.1, 1294.2, 1452.4, 1610.5, 1728.9, 2872.4, and 2931.9 $cm^{-1}$. At these positions, the Raman scattering intensity of Hf/Al co-doped silica fiber is significantly enhanced, Raman peak intensity of Hf/Al co-doped special silica optical fiber is approximately 2.4 times more than that of conventional single-mode optical fiber at 440.5 $cm^{-1}$, 2.3 times at 490.6 $cm^{-1}$, 2.1 times at 600.7 $cm^{-1}$, 2.4 times at 823.6 $cm^{-1}$ and 1005.1 $cm^{-1}$, 2.5 times at 1452.4 $cm^{-1}$, 2.3 times at 1610.5 $cm^{-1}$, 4 times at 2872.4 $cm^{-1}$, and 3.3 times at 2931.9 $cm^{-1}$. It indicates that doped hafnium ion and aluminum ion can enhance the Raman scattering intensity. Compared with Hf-doped fiber, Raman scattering enhancement effect of Hf/Al co-doped silica fiber is more obvious. When the core is doped with aluminum ions, Raman scattering intensity is significantly enhanced at 490.6 $cm^{-1}$ and 600.7 $cm^{-1}$.

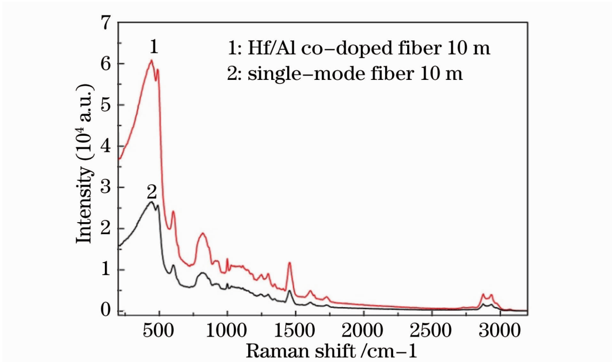


Fig. 3 Comparison between Raman spectra of Hf/Al co-doped silica fiber and conventional single-mode optical fiber

It can be seen from the experimental results that different materials doped in the core of silica fiber will change the optics property of the optical fiber, because the molecular structure and energy level structure of the fiber materials are different. This is performed as the different RSCS at the micro, and the different refractive index distribution at the macro. RSCS directly related to the Raman scattering intensity, indicates the probability of the incident photon scattering in the space angle. Thus doping different materials will affect the Raman scattering intensity, selecting doped special materials, and using appropriate fabricating technology will obtained the special Raman enhancement optical fiber. By doping Hafnium in the core of the silica fiber, the refractive index profile of the optical fiber is changed and the RSCS is increased, thereby a good Raman scattering enhancement effect could be achieved.

## 4 Conclusion

In conclusion, the Raman spectra of Hf-doped silica fiber and Hf/Al co-doped silica fiber are measured and compared with conventional single-mode fiber. The experimental results indicate that the silica optical fiber doped Hf ions in the core has obvious Raman enhancement effect. This reveals that selecting a specific doping material such as rare earth metals, and using appropriate process to be incorporated into the conventional silica fiber could be possible to obtain a special Raman enhancement optical fiber, which is very valuable for the application of non-linear optical devices.

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