Excellent Mechanical Properties of the Silicate Glasses Modified by CeO$_2$ and TiO$_2$: a New Choice for High-Strength and High-Modulus Glass Fibers

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Abstract
High-strength-modulus glass fiber is widely used in military, transportation, electronics, chemical industry, environmental protection and other industries. In recent years, with the development of new energy, the research of high-strength-modulus glass fiber which can be applied in the large size fan blade is gradually being paid attention to. It is important to find an excellent glass component for the production of high-strength glass fibers. As is well known, silicate glass has a stable glass-forming region and mature drawing processes into fibers. In this study, to obtain enhanced mechanical properties, glasses with a composition of SiO$_2$-Al$_2$O$_3$-MgO-CaO-B$_2$O$_3$-Fe$_2$O$_3$ were synthesized using TiO$_2$ and CeO$_2$. When the amount of TiO$_2$ and CeO$_2$ is less than 2 wt%, the mechanical properties increase with increases in the TiO$_2$ and CeO$_2$. However, as the amount of TiO$_2$ and CeO$_2$ increases from 2 to 3.5 wt%, the mechanical properties decrease. Co-doping with 1 wt% TiO$_2$ and 1 wt% CeO$_2$ was found to be the optimum approach, with a density of 2.626 g/cm$^3$, bending strength of 108.36 MPa, compression strength of 240.18 MPa, and compression modulus of 115.03 GPa, respectively. The optical band gap and Raman spectroscopy proved that, as long as the content of oxygen bonds reaches the maximum level, a kind of best structural stability and mechanical properties will be achieved. Hence, this high-strength-modulus silicate glass can be used to make optical fibres for military defence, wind power generation and transportation.

Keywords High-strength-modulus glass fiber · SiO$_2$-Al$_2$O$_3$-MgO glasses · TiO$_2$ · CeO$_2$ · Mechanical properties

1 Introduction
Glass fiber is an inorganic non-metallic material, according to the glass composition can be divided into: non-alkali, medium-alkali, high-alkali, alkali-resistant, high strength and high elastic modulus glass fiber, etc. During the recent decades, high-strength-modulus glass fibers have been widely used in aerospace, military defense, wind power generation, transportation, and sports, among other applications [1–3]. The properties of glass fiber drawn from different glass fractions vary considerably. Quartz glass has a series of advantages such as high temperature resistance, good chemical stability, high strength and low expansion coefficient, etc. The prepared glass fiber has the advantages of high strength and high modulus, good chemical stability, good fatigue resistance, high temperature resistance and good impact resistance compared with ordinary non-alkali E-glass fiber. The main components of high strength glass fibers are SiO$_2$, Al$_2$O$_3$, MgO and CaO, which can be modified by adjusting the composition ratio and adding transition group metal oxides and rare earth oxides. Currently, SiO$_2$-Al$_2$O$_3$-MgO glass fibers, which are high in tensile strength, elastic modulus, and impact resistance, among similar products, have received increased attention in the global manufacturing market [4–7]. However, few recent studies have reported the influence of the composition on the mechanical properties of SiO$_2$-Al$_2$O$_3$-MgO glass, let alone the influence of different additives on the mechanical properties of such glass.

The mechanical properties of glass fibers are in close contact with the different additives in the glasses. In order to improve performance, appropriate stabilizers such as rare earth oxides and transition metals are usually introduced into the glass matrix [8, 9], among which CeO$_2$ is a typical case.

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Similar to Al<sub>2</sub>O<sub>3</sub>-B<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> glasses doped with CeO<sub>2</sub>, the network structure is improved as the amount of CeO<sub>2</sub> increases at under 0.4 mol% [10]. Research shows that in barium titanium silicate glass, as CeO<sub>2</sub> doping Ce<sup>4+</sup> aggregation effect becomes more and more obvious, this phenomenon improves the network structure of the glass, and the best effect is achieved when CeO<sub>2</sub> doping amount is 2 mol% [11]. It was also found that the number of bridging oxygen bonds are generated in aluminosilicate glass at a doped molar concentration of 3.5% CeO<sub>2</sub> and CeF<sub>3</sub>, achieving the maximal thermal stability [12]. Cerium presents two different valence states: Ce<sup>3+</sup> and Ce<sup>5+</sup>, due to a ceric-cerous redox equilibrium in a glass structure. A moderate amount of Ce<sup>4+</sup> inside the glass can avoid the trapping of electrons produced through a reaction and absorb free electrons, thereby obstructing the formation of permanent defect centers and improving the properties of the glass [13, 14].

In addition, an excessive amount of CeO<sub>2</sub> will produce a series of crystallizations as well as non-bridging oxygen, thereby inducing a negative effect on the mechanical properties and drawing process of the glass. It is therefore necessary to add an oxide to make up for the defects of CeO<sub>2</sub>. The valence states of titanium result in TiO<sub>2</sub> playing an important role in the structural properties of glass, suppressing the reduction of Ce<sup>4+</sup> into Ce<sup>3+</sup> as well as a decrease in the amount of free oxygen, titanium enters the glass network by [TiO<sub>4</sub>] tetrahedral structure as a network intermediate and promotes the connectivity of glass network, thereby increasing the chemical and mechanical properties [15, 16]. Moreover, it has been suggested that, in a combined incorporation of the cerium and titanium oxides in Li<sub>2</sub>O-Bi<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> and Na<sub>2</sub>O-Bi<sub>2</sub>O<sub>3</sub>-P<sub>2</sub>O<sub>5</sub> glass, a proper mixing can significantly improve the mechanical properties [17–19].

According to the relatively outstanding properties of SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub>-MgO glass and its application prospects in glass fiber, the effects of TiO<sub>2</sub> and CeO<sub>2</sub> doping on the mechanical properties of SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub>-MgO glass when changing the amounts of TiO<sub>2</sub> and CeO<sub>2</sub> are discussed herein.

## 2 Experimental Procedure

### 2.1 Sample Preparation

The glass samples with mass concentrations of 61 wt% SiO<sub>2</sub>–9 wt% Al<sub>2</sub>O<sub>3</sub>–24 wt% MgO–5 wt% CaO–0.9 wt% B<sub>2</sub>O<sub>3</sub>–0.1 wt% Fe<sub>2</sub>O<sub>3</sub> doped with x wt% TiO<sub>2</sub>–y wt% CeO<sub>2</sub> (x = 0, 0.5, 1, 1.5, and 2; y = 0, 0.5, 1, 1.5, and 2) were prepared. High-purity SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, MgO, CaO, B<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, and CeO<sub>2</sub> powders were used in the experimental processes as shown in Table 1. The starting powders were heated at 1650 °C for 5 h in pure silica crucible until it melts. Pour the melts onto a steel plate which is preheated at 500 °C and then annealed for 2 h at approximately 850 °C to remove mechanical stress inside glass. The annealed glass is cooled in the furnace at 25 °C. Finally, all as-prepared samples were cut into a size of 30.00 mm × 3.00 mm × 3.00 mm (strips) and 10.00 mm × 10.00 mm × 2.00 mm (flakes), which were optically polished prior to measurement.

### 2.2 XRD Measurements

To confirm the amorphous state of the glass sample, an X-ray diffraction (XRD) analysis was used. The XRD spectra were recorded within a Bragg angle 2θ of 10° to 70° in a diffractometer (D2 PHASER) using Cu radiation with a scanning speed of 0.05° per second.

### 2.3 Raman Spectra and Optical Band Gap

The Raman measurement was performed using the 785 nm line of a Renishaw high-power diode laser as the excitation source working at 1.0 W. The measurement was conducted using a DILOR XY triple spectrometer equipped with the 1800 g/mm holographic grating and a CCD detector, using liquid N<sub>2</sub> cooling. The measurement was performed under an Olympus microscope with backscattering geometry, and the glass was recorded at room temperature using a fiber-optic UV-visible spectrometer (model AVASPEC 3648) within the range of 200–800 nm. Glass’s absorption of ultraviolet and visible light excites oxide ions to higher energy levels. The absorption coefficient is derived from the formula. (1) [20] can be used to calculate the optical band gap as a function of the wavelength in the ultraviolet-visible spectral range. The optical band gap reflects the structural information of the glass network, where α, T and t are absorption coefficients, transmittance (%) and glass thickness.

| Table 1 Chemical composition of glass (wt/%) |
|---------------------------------------------|
| Sample | SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub>-MgO system glasses | CeO<sub>2</sub> | TiO<sub>2</sub> |
| SAM-1  | 61 | 18 | 15 | 5 | 0.9 | 0.1 | 0 | 0 |
| SAM-2  | 61 | 18 | 15 | 5 | 0.9 | 0.1 | 0 | 0.5 |
| SAM-3  | 61 | 18 | 15 | 5 | 0.9 | 0.1 | 1 | 0 |
| SAM-4  | 61 | 18 | 15 | 5 | 0.9 | 0.1 | 0.5 | 0 |
| SAM-5  | 61 | 18 | 15 | 5 | 0.9 | 0.1 | 1 | 0 |
| SAM-6  | 61 | 18 | 15 | 5 | 0.9 | 0.1 | 1 | 1 |
| SAM-7  | 61 | 18 | 15 | 5 | 0.9 | 0.1 | 1 | 1.5 |
| SAM-8  | 61 | 18 | 15 | 5 | 0.9 | 0.1 | 1.5 | 1.5 |
| SAM-9  | 61 | 18 | 15 | 5 | 0.9 | 0.1 | 1.5 | 2 |
| SAM-10 | 61 | 18 | 15 | 5 | 0.9 | 0.1 | 2 | 2 |
\[ \alpha = \frac{-\ln T}{T} \]  

The amorphous material model proposed by Mott and Davis quantitatively correlates the linear absorption coefficient \( \alpha \) with the incident photon energy \( E \), as shown in Eq. (2) [21, 22], so the photon energy \( E \) is equal to \( \frac{hc}{\lambda} \), where \( B \), \( E_{\text{opt}} \), \( c \), \( \lambda \) and \( h \) are constants, and the optical band gap, light speed, wavelength and slab constant are respectively.

\[ \alpha E = B(E-E_{\text{opt}})^{1/2} \]  

The transformation of Eq. (2) A linear relationship between \( \alpha \) and \( \frac{hc}{\lambda} \) is generated, and the optical band gap \( E_{\text{opt}} \) is estimated by using the intercept on the horizontal axis by extrapolating the linear graph to the zero coordinate.

### 2.4 Characterization of Mechanical Properties

At room temperature, a sensitive microbalance using deionized water as the immersion liquid uses the standard Archimedes principle to measure the density of glass samples. The molar oxygen packing density (OPD) is calculated using Eq. (3) [23], where \( \rho \), \( M \) and \( C \) are the density, average molecular weight and number of oxygen molecules of each formula unit respectively.

\[ \text{OPD} = 1000C\left(\frac{\rho}{M}\right) \]  

Then use the WDW-2E universal testing machine to measure the bending strength. The results of the bending strength experiments can be calculated using Eq. (4) [24, 25], where \( L \), \( b \), \( t \), \( F \), and \( B \) respectively, are the length, width, thickness, yield stress, and bending strength of the samples.

\[ B = \frac{3FL}{2bt^2} \]  

In addition, the compression modulus was measured using a CMT5105 electromechanical universal testing machine, and calculated through Eqs. (5) and (6) [26], where \( b \), \( t \), \( F \), \( \sigma \), \( \varepsilon \), and \( E_c \) are the width, thickness, yield stress, compression strength, strain, and compression modulus of the samples, respectively.

\[ \sigma = \frac{F}{bt} \]  

\[ E_c = \frac{\sigma}{\varepsilon} \]  

Various factors such as multiple internal transmittances of the transducer and microcracks on the sample surface may affect the accuracy of ultrasonic mechanical performance indicators. Therefore, all glass samples were polished with SiC paper at up to 1200 grit, and then ultrasonically cleaned with distilled water to ensure uniform parallelism, flatness and smoothness. The average of the six samples is used as the result of the above test.

In order to quantitatively evaluate the deviation, the error based on the standard deviation reflects the error of bending strength, compressive strength and compressive modulus. The equation is expressed as follows [27, 28]:

\[ \sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (X_i - \bar{X})^2} \]  

### 3 Results and Discussion

#### 3.1 Phase Structure Analysis

Some correlation theories show that the additives particularly TiO\(_2\), CeO\(_2\), and Y\(_2\)O\(_3\) may destroy the internal structure of the glass and affect its structural stability. These metal or rare earth oxides have large ionic radii and electron densities, which may result in crystallization, decreasing the mechanical properties of the glass after drawing [29, 30]. As shown in Fig. 1, to judge whether glass doped with TiO\(_2\) and CeO\(_2\) shows an interior crystallization, the XRD patterns of the glass are used. Such patterns reveal that no crystalline phase in the glass, thereby proving that the addition of TiO\(_2\) and CeO\(_2\) will not adversely induce crystallization.

#### 3.2 Raman Spectra and Optical Band Gap

In the Raman spectra of glass at room temperature, as shown in Fig. 2, dominating peaks at approximately 950 and 1150 cm\(^{-1}\) can be seen in all compositions. The antisymmetric
vibration of Si-O_{nb} produces a strong and wide frequency band at 950 cm$^{-1}$, while the symmetrical tensile vibration of Si-O-Si produces a high frequency band at about 1150 cm$^{-1}$, both of which characterize the number of oxygen bonds within the glass [6, 31]. In addition, the internal bridge of oxygen bonds can indicate the stability of the silicate glass [32]. When the amounts of CeO$_2$ and TiO$_2$ range from 0 wt% to 2 wt%, as the intensities of the anti-symmetric vibrations of Si-O$_{nb}$ and the symmetric stretching vibrations of Si-O-Si increase with the amounts of CeO$_2$ and TiO$_2$, the number of bridging oxygen bonds in the glass continuously increases and the peak intensity at 950 and 1150 cm$^{-1}$ of SAM-6 reaches the maximum value, resulting in an enhanced network structure of the glass. Meanwhile, because the amounts of CeO$_2$ and TiO$_2$ are

Fig. 2 Raman spectra of glass doped with different amounts of TiO$_2$ and CeO$_2$. The illustration shows the positional changes of the two main peaks

Fig. 3 (a) Optical transmittance of glass doped with different amounts of TiO$_2$ and CeO$_2$, (b) linear fitting graph of different samples doped with TiO$_2$ and CeO$_2$, and (c) cut-off wavelength of optical band gap of glass doped with different amounts of TiO$_2$ and CeO$_2$
greater than 2 wt%, the decrease in the Raman intensity indicates a disruption of the glass network structure.

The transmission spectra of different glass components are shown in Fig. 3(a). According to the result of Fig. 3(a), a linear fitting graph of the transmittance spectra is characterized in Fig. 3(b), and the values of the cut-off wavelength and the optical band gap values \( E_{\text{opt}} \) of the glass are shown in Fig. 3(c). From Fig. 3(c), \( E_{\text{opt}} \) decreases with increases in TiO₂ and CeO₂ when their amounts are less than 2 wt%, whereas it increases when their amounts increase from 2 wt% to 2.5 wt%. SAM-6 was doped with 1 wt% TiO₂ and 1 wt% CeO₂, and the sample had the smallest optical band gap value of 4.38 eV. These results are consistent with those of the Raman spectra shown in Fig. 2. In general, in a silicate glass system, a lower \( E_{\text{opt}} \) indicates a more compact network structure of the glass \([14, 33]\). In addition, TiO₂ and CeO₂ change the number of bridge bonds, thereby changing the optical band gap of the glass. Moreover, CeO₂ and TiO₂ coexist in the glass thermodynamically for a redox reaction, as shown in Eq. (8) \([34]\).

\[
2\text{CeO}_2 + \text{Ti}_2\text{O}_3 = 2\text{TiO}_2 + \text{Ce}_2\text{O}_3 \Delta G_{1773K} = -71.78 \text{kJ/mol}
\]

(8)

Figure 4 shows examples of X-ray photoelectron spectroscopy (XPS). For the Ce(0)Ti(0.5) sample, minor peaks observed at 457.1–457.9 and 461.5–462.8 eV are related to Ti³⁺ \([35]\). With increases in the amounts of CeO₂ and TiO₂, major peaks observed at 459.1–459.3 and 464.8–465.0 are assigned to Ti⁴⁺, which indicates that Ti³⁺ will react to generate a large amount of Ti⁴⁺, and tetrahedral Ti-O can enter the Si-O network, enhance the interconnectivity of structural units. In this case, the expanded network opening due to the severe deformation of the [SiO₄] tetrahedron is related to the large amount of [TiO₄] and the charge balance between the substitution of Al and Si in the octahedral sites and the substitution of Si by Al in the tetrahedral sites, which simultaneously facilitates the entering of [AlO₄] into network \([36]\). This further increases the number of bridge oxygen bonds, thus increasing the degree of structural cross-linking of the glass. However, the increases in the cerium and titanium concentrations sequentially carry off a large number of bridge oxygen bonds, as shown in Eq. (9) \([37]\).

\[
\text{CeO}_2 \xrightarrow{\Delta} \text{Ce}_2\text{O}_3 + [\text{O}]\uparrow
\]

(9)

3.3 Volume Density and Oxygen Packing Density

Based on Table 2, the volume and oxygen packing densities of the different glasses are shown in Fig. 5. It can be inferred from Fig. 5 that the volume and oxygen packing densities vary from 2.401 to 2.626 g/cm³ and 73.423 to 78.725 mol/l, respectively.

| Sample | C (number) | M (g/mol) | Volume density \( \rho \) (g/cm³) | OPD (mol/l) |
|--------|------------|-----------|----------------------------------|-------------|
| SAM-1  | 1.807      | 59.090    | 2.401 ± 0.009                     | 73.423      |
| SAM-2  | 1.817      | 59.489    | 2.522 ± 0.017                     | 77.030      |
| SAM-3  | 1.827      | 59.889    | 2.572 ± 0.013                     | 78.463      |
| SAM-4  | 1.817      | 59.951    | 2.547 ± 0.014                     | 77.195      |
| SAM-5  | 1.827      | 60.811    | 2.571 ± 0.019                     | 77.243      |
| SAM-6  | 1.847      | 61.610    | 2.626 ± 0.022                     | 78.725      |
| SAM-7  | 1.857      | 62.009    | 2.519 ± 0.013                     | 75.437      |
| SAM-8  | 1.867      | 62.870    | 2.514 ± 0.018                     | 74.656      |
| SAM-9  | 1.877      | 63.730    | 2.508 ± 0.012                     | 73.867      |
| SAM-10 | 1.867      | 62.409    | 2.396 ± 0.015                     | 71.678      |
respectively. Among all glass samples, SAM-6 has maximum values of 2.626 g/cm$^3$ and 78.725 mol/l, individually. The results of these two variables indicate show a similar trend in which both the volume and oxygen packing densities increase with an increase in the amounts of TiO$_2$ and CeO$_2$ when the content is less than 2 wt%, whereas a continuous decrease occurs when the content is higher than 2 wt%. As shown in Figs. 2 and 3(c), the Raman intensity increases and the optical band gap decreases as the amounts of TiO$_2$ and CeO$_2$ increase from 0 wt% to 2 wt%, which indicates the presence of numerous bridge oxygen bonds inside the glass, thus improving the bending strength. The attractive force generated by Ce$^{4+}$ increases the bonding strength between metal cations and oxygen ions in the glass, enhancing the bonding force of ionic bonds, thus improving the bending strength of the glass [37, 38]. In addition, when there are enough oxygen atoms to provide a connection, Ti$^{4+}$ is beneficial to improve the interconnection of the glass network when it enters the glass tetrahedral structure, thereby improving the bending strength of the glass [36]. However, as the amount of TiO$_2$ and CeO$_2$ increases from 2 to 3.5 wt%, the bending strength decreases. In this context, an excessive amount of CeO$_2$ will generate more free oxygen, as shown in Eq. (8), resulting in an excessive number of non-bridging oxygen bonds. Ce$^{3+}$ ions can break the chemical bond and decouple the glass network, while Ce$^{4+}$ ions can connect the broken glass network in the form of tetrahedra, increasing the chemical stability and mechanical properties of the glass [39].

According to the previous section, when the CeO$_2$ content is too high, the glass system is dominated by Ce$^{3+}$. Meanwhile, the presence of trivalent cerium makes it difficult to bond with four-coordinated Ti-O units according to Pauling rules, and thus the titanium may act as a network intermediate. However, an increase in TiO$_2$ may result in an increase in non-bridge and bond defects. This then depolymerizes the network by breaking up the Si-O bonds, which induces an increase in

### Table 3: Bending strength, compression strength, and compression modulus of the glass

| Sample | Bending strength (MPa) | Compression strength (MPa) | Compression modulus (GPa) |
|--------|------------------------|---------------------------|--------------------------|
| SAM-1  | 77.04 ± 2.21           | 181.49 ± 3.24             | 106.70 ± 2.06            |
| SAM-2  | 96.67 ± 2.75           | 214.88 ± 4.65             | 109.71 ± 2.19            |
| SAM-3  | 100.56 ± 1.23          | 240.15 ± 2.07             | 111.71 ± 3.33            |
| SAM-4  | 98.56 ± 4.05           | 223.11 ± 3.56             | 110.05 ± 4.48            |
| SAM-5  | 102.04 ± 1.36          | 237.10 ± 5.49             | 111.06 ± 1.13            |
| SAM-6  | 108.36 ± 3.07          | 240.21 ± 4.01             | 115.06 ± 3.20            |
| SAM-7  | 94.19 ± 4.88           | 231.99 ± 2.46             | 108.66 ± 1.26            |
| SAM-8  | 93.15 ± 1.38           | 219.69 ± 4.60             | 107.53 ± 2.75            |
| SAM-9  | 91.55 ± 2.45           | 215.05 ± 2.29             | 103.51 ± 3.35            |
| SAM-10 | 86.73 ± 3.96           | 200.00 ± 4.21             | 85.67 ± 4.76             |

### 3.4 Mechanical Properties

Table 3 and Fig. 6(a) show the bending strength of glass doped with different amounts of TiO$_2$ and CeO$_2$. It can be seen that SAM-6 achieves the maximum bending strength at 108.36 Mpa. Meanwhile, the glass bending strength increases with the increase of TiO$_2$ and CeO$_2$ content (total less than 2 wt%), and both Raman strength and oxygen packing density increase with the incorporation of CeO$_2$ and TiO$_2$, which indicates the presence of numerous bridge oxygen bonds inside the glass, thus improving the bending strength. The attractive force generated by Ce$^{4+}$ increases the bonding strength between metal cations and oxygen ions in the glass, enhancing the bonding force of ionic bonds, thus improving the bending strength of the glass [37, 38]. In addition, when there are enough oxygen atoms to provide a connection, Ti$^{4+}$ is beneficial to improve the interconnection of the glass network when it enters the glass tetrahedral structure, thereby improving the bending strength of the glass [36].
the number of microcracks and pores. The structure is unable to resist the external pressure and thus reduces the bending strength of the glass [40].

The compressive strength and modulus of glass doped with different amounts of TiO2 and CeO2 are shown in Table 3 and Fig. 6(b). It can be seen that SAM-6 possesses the maximum compression strength and compression modulus of 240.21 MPa and 115.06 GPa, respectively. Meanwhile, the compression strength and compression modulus increase with increasing amounts of CeO2 and TiO2, which range from 0 wt% to 2 wt%, when the decreases in the amounts of CeO2 and TiO2 are more than 2 wt%. The above laws are clearly consistent with the bending strength of the glass.

### 3.5 Microscopy

The glass fraction doped with 1 wt% CeO2 and 1 wt% TiO2 according to the above is made into glass fibers by the leaky plate drawing method. The SEM image of the glass fibers are shown in Fig. 7, the number of defects on the surface of the glass fiber is an important factor affecting its mechanical properties, as can be seen in Fig. 7, there are no more obvious defects on the surface of the glass fibers.

### 4 Conclusions

The influence of TiO2 and CeO2 on the mechanical properties of 61 wt% SiO2–9 wt% Al2O3–24 wt% MgO-5 wt% CaO-0.9 wt% B2O3–0.1 wt% Fe2O3–x wt% TiO2–y wt% CeO2 glass was investigated. When the amounts of TiO2 and CeO2 are less than 2 wt%, the Raman intensity increases and the optical band gap decreases with increasing amounts of CeO2 and TiO2, which range from 0 wt% to 2 wt%, when the decreases in the amounts of CeO2 and TiO2 are more than 2 wt%. The above laws are clearly consistent with the bending strength of the glass.

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### Availability of Data and Material

Not applicable.

### Author Contributions

All of the authors contributed to the idea, simulation of the research, the analysis of the results, and the writing of the manuscript.

### Declaration

The authors declare that they have no conflict of interest.

### Consent to Participate

Not applicable.

### Consent for Publication

Not applicable.

### Competing interests

The authors declare no competing interests.

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