The role of dysprosium ions as a dopant on linear and nonlinear optical dispersion parameters in a-Se thin film
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ABSTRACT
Thin films of un-doped and doped a-Se with Dysprosium rare-earth ions have been prepared by the thermal evaporation technique. The optical transmission spectra of the investigated films have been measured in a wide spectral range and used to calculate the linear optical constants together with the optical energy gap of studied films. The observed decrease in the values of the energy gap against the increase of the Dysprosium (Dy) content in a-Se films has been explained using Mott and Davis Model and in terms of electronegativity difference of the constituent atoms. Furthermore, the dispersion of nonlinear parameters such as second-order refractive index and nonlinear absorption coefficient (two-photon absorption coefficient) of investigated films are presented and discussed.

Keywords: Selenium Thin Films; Doping of Selenium; Rare Earth; Optical Properties of Doped Selenium

1. Introduction
Rare-earth (RE)-doped glass fiber amplifiers operating at a 1.3 μm wavelength band have received extensive attention due to the zero-dispersion of the silica fiberglass in the 1.3 μm-wavelength region, and most installed fibers worldwide are optimized at this wavelength[1-4]. In contrast, Dysprosium rare-earth atoms, Dy which have an active unfilled f shell in its electronic configuration ([Xe] 4f104s2), can provide 1.3 μm emission due to the 6F11/2, 6H9/2 → 6H15/2 transition[5]. In addition, Dy has a good absorption band at approximately 800 nm, at which level a cheap commercial laser diode could be used for excitation. On the other hand, amorphous Selenium (a-Se) is characterized by the existence of localized states in its mobility gap. These states are created due to the presence of structural defects and the absence of long-range order[6-8]. The structural disorder made a-Se and its alloys have high optical transparency in the infra-red (IR) spectral regions up to 10 μm. Besides, it has a large refractive index, thermal stability, and a high degree of covalent bonding. Furthermore, due to high rare-earth solubility, high emission quantum efficiency[9], and the low phonon energy (~ 250 cm⁻¹) of amorphous selenides compared with fluorides (~ 550 cm⁻¹), or oxide glasses (~ 1100 cm⁻¹)[10], it could be used as a suitable host medium for Dy ions to enhance its mid-IR laser emission. It should be noted that the low phonon energy of a-Se decreases the multi phonon relaxation which enables an active transition between rare-earth atom levels in the middle IR spectral region. Consequently, the exploration of the optical properties of doped a-Se with Dy ions is very important to improve the performance of Laser emission[11].
In the previous work\textsuperscript{12}, the study of Selenium films was intended to have a comprehensive understanding of the influence of Dysprosium (Dy) ion dopant on the ac conductivity and dielectric parameters of a-Se films. The present aims to gain a better investigation on the effect of doping with Dy on the optical dispersion relations of the complex dielectric constant, optical energy gap, and material dispersion. Furthermore, the effect of doping of a-Se with Dy ions on second-order refractive index and two-photon absorption is calculated and discussed.

2. Experimental details

Bulk selenium doped with Dysprosium with ratios 0.008 and 0.01 at. % were prepared by mixing suitable proportions of Se and Dy, of purity 5 N, in a silica tube sealed at 10-5 Torr. The mixture was heated in an electric furnace up to 950 °C and kept at that temperature for 9 h. The obtained bulk ingots are used as source material to prepare thin films by the thermal evaporation technique. More details about bulk and thin films preparation of Se doped Dy are given elsewhere\textsuperscript{12}. After evaporation, the thickness of the fresh films was accurately determined by an optical interference method and is found to be in the range of 750-804 nm.

The structural phase of as-prepared thin film samples has been identified using an X-ray diffraction pattern (XRD) computerized system (model: Philips EXPERT-MPDUG PW-3040 diffractometer with Cu Kα radiation source). The computer-aided two-beam spectrophotometer of type Shimadzu-3101PC UV-VIS-NIR, is used to record the optical transmittance ($T$) as a function of wavelength ($λ$) for the investigated films. A resolution limit of 0.2 nm and a sampling interval of 2 nm was utilized for recording the different measuring points. The accuracy of measuring $T(λ)$ is 0.003 with the incident beam at normal incidence to the film surface. The optical measurements were carried out at room temperature in the spectral region of 500-2500 nm.

3. Results and discussion

The recorded XRD patterns for the studied as-prepared a-Se, previous work of SeDy\textsubscript{0.008} films\textsuperscript{12}, and the present work [p. w.] of Se films doped with 0.01 at. % with Dy is shown in Figure 1. In this figure, the XRD pattern of the fresh Se films reflects its amorphous nature. The observed diffraction peaks in case of Se doped with 0.008 at. % Dy\textsuperscript{12} means the growth of the crystalline phase at the expense of an amorphous state. This crystalline phase consists of mixed phases of elemental Se, Dy, and tetragonal and orthorhombic structures of SeDy as shown in Figure 1. Furthermore, increasing the Dy content in a-Se up to 0.01 at. % increased the intensity of the diffraction peaks for (102) of Dy and (002), (003), and (112) phases for SeDy which means that increasing the growth of crystalline zones in SeDy\textsubscript{0.01} as shown in Figure 1.

![Figure 1. XRD pattern for a-Se, previous work of SeDy\textsubscript{0.008}(12) and the present work [P.W.] of SeDy\textsubscript{0.01} thin films. It should be noted that the diffraction pattern of SeDy\textsubscript{0.008}(12) is added to the figure for the sake of comparison.](image)

3.1 Linear optical dispersion

The linear (weak field) optical constants such as refractive index ($n$), extinction coefficient ($k$), and optical energy gap, $E_g$, are considered as key parameter for optimizing the optical properties of a given optical application\textsuperscript{13}. The measured optical transmission against wavelength is used to evaluate the
linear constant $n$ and $k$ for un-doped and Dy-doped Se-films using the Swanepoel method\cite{14-16}.

The dependence of the calculated linear optical constants $n$ and $k$, on the applied wavelength for the studied samples is shown in Figure 2. In Figure 2a the Cauchy fitted values of $n$ show a decrease against wavelength and an increase in the magnitude as the doping level of Dy increase in the structural network of a-Se. The dependence of the extinction coefficient ($k$) on $\lambda$ shown in Figure 2b illustrates a decrease in exponential trend as $\lambda$ increases and an increase against the doping content with Dy in a-Se films.

Figure 3 shows the refractive index as a function of composition for the investigated a-Se doped with Dy rare-earth ions films together with those published in literature at $\lambda = 1.3$ µm using different preparation techniques. The general trend of the function is the increase of $n$ against Dy content ratio in at. %. However, the discrepancy among the data published by assorted authors is attributed to the variation in the preparation techniques used in formulating the studied materials in each reference besides the dependence of the properties of chalcogenides on its thermal history. In reference\cite{17} bulk samples are prepared by conventional melt quenching technique for the mixture of the constituent elements. The obtained ingots are annealed at their glass transition temperature before any measurements. Furthermore, in reference\cite{18} the obtained melt quenched ingots are used as source material to prepare thin film samples using KrF excimer laser operating at 248 nm.

![Figure 2. Variation of refractive index ($n$) (a) and extinction coefficient ($k$) (b) with wavelength ($\lambda$) for studied amorphous Se, c-SeDy$_{0.008}$ and c-SeDy$_{0.01}$ thin films.](image)

![Figure 3. The variation of refractive index as a function of the doped Dy rare-earth ions in at. % for the present work [P. W.].](image)

![Figure 4. The calculated absorption coefficient ($\alpha$) as a function of photon energy ($h\nu$) for the studied films. The dashed horizontal line differentiates between the Tauc and Urbach regions.](image)
The dependence of the optical absorption coefficient ($\alpha$) calculated using values of the extinction coefficient in Figure 2b on the incident photon energy of the investigated films is shown in Figure 4. This figure confirms that for all studied samples the value of $\alpha$ increases against photon energy in an exponential trend and shifted towards lower energy as doping rate increases in the structural network of a-Se films. This shift indicates that the absorption edge decreases in energy (redshift in wavelength) against the increase of doping level of Dy.

Each curve recognized in Figure 4 could be divided into two different regions\cite{19,20}:

The first region is for the high absorption, namely for $\alpha(h\nu) > 10^4$ cm$^{-1}$ (Tauc region). The optical absorption in this region could be described by Tauc’s relation\cite{19}:

$$\alpha(h\nu) = A(h\nu - E_g)^r$$

(1)

where $A$ is constant, $E_g$ the optical band gap and $r = 1/2$ as well as 2 for direct and indirect transitions in sequence. According to Eq. (1), the dependence of $(\alpha h\nu)^{1/r}$ versus $h\nu$ is shown in Figure 5 for both values of $r$. For each composition, the energy gap $E_g$ is calculated by fitting the function $(\alpha h\nu)^{1/r} = f(h\nu)$, locally point by point to the linear regression line and extrapolating to $y = 0$ yields the value of $E_g$. The results are given in Table 1 as a function of the film’s composition. According to Table 1, it is observed that the value of optical band gap $E_g$ decreases against an increase of Dy content through the considered range of doping 0.008-0.01 at. % of Dy.

![Figure 5](image)

**Figure 5.** Tauc’s plots for determining the optical energy gap of direct (a) and indirect (b) transitions for films investigated.

The decrease $E_g$ against the increase of Dy content in the structure network of a-Se can be explained using the electronegativity of the elements involved. The electronegativity of Se and Dy are 2.55 and 1.22.
respectively and Dy has a lower electronegativity than Se. The valence band of a-Se contains the lone pair p-electrons and the addition of an element with lower electronegativity (Dy) to a higher electronegative element (Se) may raise the energy of lone pair states, which is further responsible for the broadening of the valance band inside the forbidden gap and leads to band tailing and hence bandgap shrinkage\cite{18}.

The second region in Figure 4 with $\alpha(h\nu) < 10^4$ cm\(^{-1}\) (Urbach region), where the absorption coefficient presents a roughly exponential behavior:

$$\alpha(h\nu) = \alpha_e \exp\left(\frac{h\nu}{E_u}\right) \quad (2)$$

Where $\alpha_e$ is a constant and $E_u$ is an energy that is often interpreted as the width of the tail of localized states in the gap region. This relation was first proposed by Urbach\cite{21}. The inverse slope or width of the exponential edge $E_u$ reflects the width of the localized band tail\cite{22} which is called Urbach energy. It determines the degree of disorder in the semiconductor which is responsible for internal potential fluctuations giving rise to tails of localized states at the band edges. The Urbach energy depends strongly on deposition conditions and annealing, which are likely to influence the disorder and therefore the band tailing\cite{23}. The calculated values of $E_u$ are given in Table 1 as a function of film composition. These values show a decrease from 0.30 eV for the undoped a-Se film to 0.25 and 0.21 eV for doping with 0.008 and 0.01 at. % in sequence. Such a decrease in the value of $E_u$ indicates a decrease in the disordered character of a-Se due to the introduction of Dy which is consistent with the obtained structure using XRD for the studied samples shown in Figure 1. consequently, a decrease of $E_u$ is attributed to the crystallized character of the thermally deposited films. Also, the existence of a band tail ($E_u$) that accompanied the localized states in the gap reflects some degree of disorder in the considered semiconductor film.

The complex dielectric constant $\varepsilon^* = \varepsilon_1 - i\varepsilon_2$ of a material in terms of the linear optical constants, $n$, and, $k$, could be written as $\varepsilon_1 = n^2 - k^2$, $\varepsilon_2 = 2nk$ where $\varepsilon_1$ is the real part, while $\varepsilon_2$ is the imaginary part. Figure 6 shows the calculated values of $\varepsilon_1$ and $\varepsilon_2$ of the complex dielectric constant versus the photon energy ($h\nu$) for the present film’s composition. Figure 6a shows a nearly exponential increase with photon energy for all investigated samples and nearly has the same trend as $n = f(\lambda)$. On the other hand, $\varepsilon_2$ illustrates a clear exponential increase of $\varepsilon_2$ against ($h\nu$) which has the same behavior as $k = f(h\nu)$. For a better

<table>
<thead>
<tr>
<th>Film Composition</th>
<th>$E_g$, eV</th>
<th>$E_u$, eV</th>
<th>$\varepsilon_\infty$</th>
<th>$\varepsilon_1 (N/m^* \times 10^{50})$</th>
<th>$\omega_p \times 10^{14}$ Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-Se</td>
<td>2.10</td>
<td>0.30</td>
<td>4.91</td>
<td>5.710</td>
<td>1.94</td>
</tr>
<tr>
<td>c-SeDy$_{0.008}$</td>
<td>1.96</td>
<td>0.25</td>
<td>5.54</td>
<td>6.079</td>
<td>2.48</td>
</tr>
<tr>
<td>c-SeDy$_{0.01}$</td>
<td>1.59</td>
<td>0.21</td>
<td>6.77</td>
<td>6.250</td>
<td>2.87</td>
</tr>
</tbody>
</table>
understanding of the optical behavior of the investigated films, it is necessary to determine some optical parameters such as dispersion of high-frequency dielectric constant and the lattice vibration modes as follows:

In the near-infrared spectral region, where the frequency is relatively low, the real \( \varepsilon_1 \) and imaginary \( \varepsilon_2 \) parts of the complex dielectric constant can be written as:

\[
\varepsilon_1 = \varepsilon_\infty \left( \frac{e^2}{4\pi \varepsilon_0 c^2 \varepsilon_m} \right)^\frac{1}{2} \left( \frac{N}{m^*} \right) \lambda^2, \quad \varepsilon_2 = \varepsilon_\infty \frac{\omega_p^2}{8\pi c^2 \tau} \lambda^2
\]

where \( \omega_p \) is the plasma resonance frequency of all the valence electrons involved in the optical transitions, \( e \) the high-frequency dielectric constant, \( e \) electronic charge, \( c \) speed of light, \( \varepsilon_0 \) free space dielectric constant, \( N/m^* \) is the ratio of free carriers density to the free carrier effective mass and \( \tau \) relaxation time. According to Eq. (3) plot of \( \varepsilon_1 \) versus \( \lambda \) and extrapolating the linear part of the plot in the high wavelength region to zero wavelength gives the value of \( \varepsilon_\infty \) and the slope of this line is used to calculate values of \( (N/m^*) \) for the investigated films. The calculated \( \varepsilon_\infty \) \( (N/m^*) \) and \( \omega_p \) are given in Table 1 as a function of investigated film compositions. The value of \( N/m^* \) reflects an increase in the free carrier density with the increase of Dy-content which is argued to be the metal character of Dysprosium rare earth.

According to the single-effective oscillator model suggested by Wemple and DiDomenico[25], the refractive index could be described by the following relation:

\[
n^2 - 1 = \frac{E_0 E_d}{E_0^2 - E^2} \quad (4)
\]

where \( E \) is the photon energy in eV, \( E_0 \) is the single oscillator energy (average oscillator energy for electrons) and \( E_d \) is the dispersion energy parameter of the material. For the magnetic chalcogenides such as the present case of Dy doped Se films, Eq. (4) could be rewritten as:

\[
n^2 - 1 = \frac{\hat{E}_d \hat{E}_0}{\hat{E}_0^2 - \hat{E}^2} + \frac{E_d E_0}{\hat{E}_0^2 - \hat{E}^2} \quad (5)
\]

where \( \hat{E}_d, \hat{E}_0 \) applies to \( f \rightarrow d \) transitions and \( E_d, E_0 \) applies to \( s, p \rightarrow d \) transitions. It is straightforward to combine terms in Eq. (5) and get the following expressions for the equivalent single oscillator parameters \( \hat{E}_0 \) and \( \hat{E}_d[25] \):

\[
\hat{E}_0^2 = \hat{E}_0^2 \left( 1 + \frac{E_d}{\hat{E}_0} \left( \frac{\hat{E}_0}{E_0} \right)^2 \right)
\]

and

\[
\hat{E}_d^2 = \hat{E}_d^2 \left( 1 + \frac{E_d}{\hat{E}_d} \left( \frac{\hat{E}_d}{E_0} \right)^2 \right)
\]

\( \hat{E}_0 \) is the dispersion energy parameter of the material and is a measure of the strength of interband optical transitions and \( \hat{E}_d \) is related to the nearest neighbor cation coordination, anion valency, ionicity, and the effective number of dispersion electrons. According to Eq. (5) Plotting \( (n^2-1)^{-1} \) versus the photon energy \( (hv)^2 \) as shown in Figure 7 and fitting the straight part of the curve in the high energy region allows to obtain from the slope and the intercept values of \( E_0 \) and \( E_d \). In the low energy region, the slope and intercept of the straight yields the values of \( \hat{E}_d \) and \( \hat{E}_0 \). The calculated values of these dispersion parameters are listed in Table 2.

![Figure 7](image-url)
decrease of this splitting as well as the crystallized nature with increasing Dy-content.

If the wavelengths are much shorter than the phonon resonance, the lattice contribution is given by:

\[ n^2 - 1 = \frac{\hat{E}_d \hat{E}_0}{E_0^2 - E^2} + \frac{E_d E_0}{E_0^2 - E^2} - \frac{E^2}{E^2}, \]  

(8)

where \( E_i \) is the lattice oscillator strength. Poignant\(^{[27]} \) has shown that at a long wavelength, where \( E^2 \ll \hat{E}_0^2 \), a plot of \( (n^2 - 1) \) versus \( 1/E^2 \) approaches a straight line and Eq. (8) has the following form:

\[ n^2 - 1 = \left( \frac{\hat{E}_d}{\hat{E}_0} + \frac{\hat{E}_0}{E_0} \right) - \frac{E^2}{E^2} \]  

(9)

The intercept of this line yield the ratio \( E_d/E_0 \) at high energy, and \( \hat{E}_d/\hat{E}_0 \) at low energy, while the slope is \(-E^2\). The obtained values of \( E_i \) are given in Table 2. The tabulated values of \( E_l \) shows variation from 0.54 eV for a-Se to 0.36 eV for c-SeDy\(_{0.008}\), and 0.38 eV for c-SeDy\(_{0.01}\) respectively.

Table 2: Values of single oscillator energy (\( E_0, \hat{E}_0 \)), dispersion energy (\( E_d, \hat{E}_d \)), lattice oscillator strength (\( E_l \)), and wavelength at zero material dispersion (\( \lambda_c \)) for investigated films composition

<table>
<thead>
<tr>
<th>Film Composition</th>
<th>( E_0, ) eV</th>
<th>( E_d, ) eV</th>
<th>( \hat{E}_0, ) eV</th>
<th>( \hat{E}_d, ) eV</th>
<th>( \hat{E}_0, ) eV</th>
<th>( \hat{E}_d, ) eV</th>
<th>( \hat{E}_0, ) eV</th>
<th>( \hat{E}_d, ) eV</th>
<th>( \hat{E}_0, ) eV</th>
<th>( \hat{E}_d, ) eV</th>
<th>( \lambda_c, ) ( \mu m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-Se</td>
<td>4.50</td>
<td>24.25</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>0.54</td>
<td>1.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c-SeDy(_{0.008})</td>
<td>3.74</td>
<td>12.62</td>
<td>2.49</td>
<td>6.34</td>
<td>3.97</td>
<td>8.36</td>
<td>0.36</td>
<td>1.66</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c-SeDy(_{0.01})</td>
<td>3.18</td>
<td>11.66</td>
<td>2.17</td>
<td>5.45</td>
<td>4.00</td>
<td>12.65</td>
<td>0.38</td>
<td>1.74</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The material dispersion \( M(\lambda) \) could be expressed in terms of the refractive index, \( n \), as:

\[ M(\lambda) = \frac{\lambda}{c} \left( \frac{d^2 n}{d\lambda^2} \right) \]  

(10)

Differentiating Eq. (8) w.r.t \( \lambda \) yields the material’s dispersion as a function of \( \hat{E}_0 \) and \( \hat{E}_d \) as follows\(^{[26]} \):

\[ M(\lambda) = 1.54 \times 10^4 \frac{\hat{E}_d/\hat{E}_0^3}{n^2 \lambda^3} - 2.17 \times 10^3 \frac{E^2 \lambda}{n} \quad (ps \text{ } nm^{-1} \text{ } km^{-1}) \]  

(11)

Figure 8 shows the graphical relation of the calculated \( M(\lambda) \) versus wavelength. The wavelength at which \( M = 0 \), and the obtained results are given in Table 2 as a function of films composition. Similarly, the value of \( \lambda_c \) can be calculated from Wemple’s three-parameter formula\(^{[26]} \):

\[ \lambda_c = 1.63 \left( \frac{\hat{E}_d}{\hat{E}_0^2 E_l^2} \right)^{\frac{1}{2}} \]  

(12)

Nevertheless, the observed variation of \( \lambda_c \) indicates that the introduction of Dy atoms in a-Se causes a shift of the material dispersion \( M(\lambda) \) towards higher wavelengths. Such a redshift represents an important parameter to improve the operational conditions and performance of optical fibers\(^{[28,29]} \). Indeed, the listed values of material dispersion in Table 2 show that the pumping of optical signals in the Selenium chalcogenide fibers at zero dispersion wavelength (ZMD) could be tuned by increasing the doping ratio of Dy\(^{[30,31]} \).

3.2 Non-Linear optical dispersion

The microscopic nonlinear properties of the chalcogenide semiconductors have been investigated through the determination of second-order refraction index, \( n_2 \) and nonlinear absorption coefficient \( \beta \).
where \( n_2 \) and \( \beta \) are expressed as

\[
n_2 = n + n_2 l
\]

and

\[
\alpha(l) = \alpha + \beta l,
\]

where \( l \) is the incident intensity, \( n \) is the total refractive index and \( n \) represents the weak-field refractive index (linear refractive index). The second-order index of refraction, \( n_2 \) is required for soliton propagation in the optical telecommunication fibers and used in all-optical switching schemes.

Boling et al.\(^{[32]}\) derived a semi-empirical relation for predicting the second-order index of refraction, \( n_2 \), for semiconductors from the linear refractive index, \( n \) which has the simplest form:

\[
n_2 (\times 10^{-13} \text{ esu}) = G \frac{n - 1}{v_d^{1/4}}
\]

(14)

where \( G \) is an empirical constant and \( G = 391\)\(^{[32]}\). Here \( v_d \) is the Abbe dispersion number and is given by:

\[
v_d = \frac{n_d - 1}{n_f - n_c}
\]

(15)

where \( n_d, n_f, \) and \( n_c \) refer to refractive indices at 589.0, 486.1, and 656.3 nm respectively.

The two-photon absorption coefficient \( \beta \) is given by\(^{[33]}\):

\[
\beta = \frac{K E_p^{1/2} F(2h\nu/E_p)}{n^2 E_s^
u}
\]

(16)

where \( K \) is the material-independent constant given by

\[
K = \frac{2^9 \pi^5 e^4}{5 c^2 [m^*_o]}
\]

(17)

Here \( e \) and \( m^*_o \) are the electron charge and its effective mass, respectively. In our calculations, \( K = 3100 \) and \( E_p \) is related to the Kane momentum parameter, \( p \), where \( E_p = 2p^2 m / \hbar^2 \) and \( m \) is the electron mass. \( F \) is a function that represents the dispersion of \( \beta \) with respect to the incident photon energy \( h\nu \). This function depends upon the band structure and determines the energy states that are coupled. The function \( F \) can be evaluated from the relation\(^{[33]}\):

\[
F(2h\nu/E_p) = \left( \frac{(2h\nu/E_p) - 1}{} \right)^{1/2} \left( \frac{2h\nu/E_s}{} \right)^{3}
\]

(18)

The overall dispersion behavior of \( \beta \), as shown in Figure 9b a ratio between the maximum nonlinear absorption coefficients of the two-photon absorption (TPA) to the optical bandgap energy equals 1.4 is observed for different chalcogenide compositions\(^{[34-40]}\). The maximum nonlinear absorption coefficient \( \beta \) for investigated films is given in Table 3. The dispersion of \( n_2 = f(h\nu) \) is be plotted as shown in Figure 9a.

![Figure 9](image_url)

**Figure 9.** Dependence of second-order refractive index, \( n_2 \) (a) and nonlinear absorption coefficient, \( \beta \) (b) on the incident photon energy, \( h\nu \) for the studied films.

<table>
<thead>
<tr>
<th>Film Composition</th>
<th>( \beta_{\text{max}} ) cm/GW</th>
<th>( E\beta_{\text{max}} ) eV</th>
<th>( E_\nu / E\beta_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-Se</td>
<td>13.6060</td>
<td>1.4739</td>
<td>1.42</td>
</tr>
<tr>
<td>c-SeDy0.008</td>
<td>16.7625</td>
<td>1.3805</td>
<td>1.42</td>
</tr>
<tr>
<td>c-SeDy0.01</td>
<td>26.631</td>
<td>1.1197</td>
<td>1.42</td>
</tr>
</tbody>
</table>

4. Conclusion

The study of the role played by dysprosium ions as a dopant in the structural network of a-Se on optical dispersion leads to draw the main following concluding remarks:
The optical band gap \((E_g)\) decreases with an increase of the Dy content which is argued to be the difference in electronegativity between Se and Dy. The variance between the values of the optical energy gaps of the studied samples and previously published data for other chalcogenide compositions doped also with Dy are attributed to the sensitivity of chalcogenides to its thermal history and preparation conditions.

The single oscillator energy, \(E_o\), showed a decrease accompanied by an increase in the values of \(E_d\). This trend of \(E_o\) and \(E_d\) shifted the material dispersion \(M(\lambda)\) towards longer wavelengths from 1.6 to 1.74 nm against the increase in the Dy-content. This shift means that the material dispersion of chalcogenide fiber could be tuned by controlling the doping ratio of Dy.

A ratio between the maximum nonlinear absorption coefficients of TPA to the optical bandgap energy equals 1.4 is observed for different chalcogenide semiconductors.

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