Realisation of pressure sensor using germanium-based photonic structure

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Germanium-based one dimensional photonic structure is proposed in the present research work to envisage pressure sensor at the signal of 1550 nm. The internal mechanism of the present works deal with numerical simulations, which relies on eight different types of losses (absorption, diffraction, dispersion, reflection, radiation, propagation, polarisation and scattering) to compute the transmitted signal emerging from the photonic structure. The sensitivity of the device is also discussed during the computation of the pressure. This pressure variation is accounted for calculating the sensitivity factor for better accuracy. The pressure in germanium-based photonic structure is determined by knowledge of the transmitted intensities.

1. Introduction

Research on photonic structure is burgeoning from time to time owing to its significant role for different applications in the field of sensing, chip design, signal processing, communication and networking etc. As far as type of photonic structure is concerned with respect to the arrangement of crystal, one dimensional photonic structure has appeared in the market in its physical form where research on a two dimensional photonic structures is undergone and it stands in developing stage [1]. However, research on three dimensional photonic structures is an infant stage due to its hinder with respect to fabrication feasibility [2]. Since one dimensional photonic crystal is realized with respect to the possibility of fabrication, the present research deals with 1D photonic structure, that acts as pressure sensor, where germanium is chosen as substrate material. The careful deposition of germanium controls the nature of defects, concentration level, and electrical polarisation which leads to enabling of design of photonic integrated circuit [3]. In addition to this, germanium-based photonic sensing is a promising area, which makes a faster impact. In this paper germanium-based photonic structure acts as pressure sensor which is able to determine the pressure up to 10 GPa with accuracy and more sensitivity. Further, moving to the literature review on photonic sensor, ample works have been found relating to the sensor [4-9]. Recently, a pressure sensor is designed in the reference [6] with the help of two dimensional photonic crystal structures. Similarly temperature and pressure sensor is realised in the reference

[7], where two types of losses have only been considered. Further, multiple sensing applications are also envisaged in the reference [8]. Apart from this, quantum well based photonic crystal pressure sensor is discussed in the reference [9]. Besides these, remarkable researches pertaining to the photonic based pressure have been disclosed in the reference [10-14]. For example, reference [10] focuses on the measurement of pressure using fiber optic microbend sensor. In this paper, crack detection is also estimated. In the reference [11], intensity modulated pressure is discussed using microbending based optical fiber with the help of Helium laser beam. Further an experimental model is discussed on fibre optic pressure sensor, which monitors the structural defects [12]. Moreover, a broad study on pressure sensor is analysed in the reference [13] for structural health monitoring. In the reference [14], different models have been realised using piezoelectric sensor for structural health monitoring system. Though the above said works render different noteworthy application with respect to the various pressure sensor, the present research deals with the one dimensional photonic structure to envisage pressure sensor.

The novelty of present work deals with eight different type losses which are frequently encountered with the photonic structure. Apart from this, it is expected that, no previous research work has dealt with such number of losses. To understand the same, the present manuscript is divided into several sections such as section 2 deals with proposed photonic structure and design of pressure sensor. Similarly section 3 manipulates with the basic numerical expressions through which one can compute the amount of

pressure associated with it. Further, the result and interpretation is made in section 4. Finally, conclusions are summarised in the section 5.

2. Pressure sensor design

The objective of present research is to estimate the amount of pressure, which is accomplished with the photonic structure pertaining to the output signal. To realise the same, let us concentrate on the Fig. 1 through which one can realise an operational mechanism.
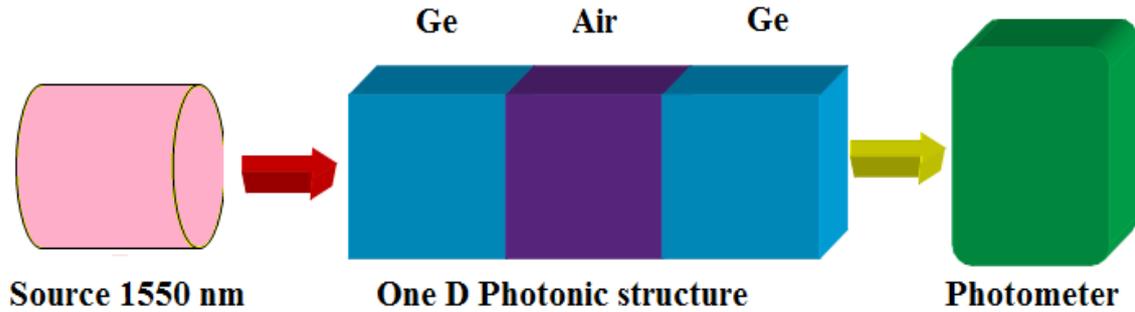
Fig. 1(a). Proposed experimental structure (color online)

Fig. 1(a) represents the proposed experimental setup through which one can estimate the pressure with respect to the output transmitted intensity. In this figure, source is assumed to be infrared sensor which produces a signal of 1550 nm whose size is in terms of nanometre and less than the proposed one dimensional photonic structure. This presumption infers that zero coupling loss is associated between source and photonic structures. In this case,

photonic structure is one dimensional structure which is the combination of germanium and an air material in odd and even position respectively. Here different length of waveguide is considered. For example, 5 different types of waveguide have been chosen. The same is shown in the Fig. 1(b).
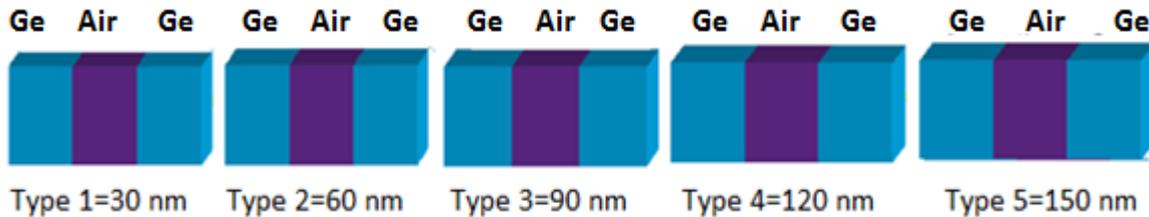
Fig. 1(b). 1Dimensional Germanium based photonic waveguide with different lengths (color online)

From the Fig. 1(b) it is found that the length of photonic waveguide of 30 nm, 60 nm, 90 nm, 120 nm and 150 nm for type 1, type 2, type 3, type 4 and type 5 respectively. The number of layer remains same (3 layers). However, thickness of each layer is changed and taken as 10 nm, 20 nm, 30 nm, 40 nm, and 50 nm for type 1, type 2, type 3, type 4 and type 5 respectively. Further, considering on operation mechanism, it is found that the signal of 1550 nm incidents to the proposed structure, then transmitted signal degrades due to suffering from several losses such as reflection, absorption, dispersion, diffraction, polarisation, propagation, scattering, radiation etc. After suffering such losses, the signal reaches at the output end, where transmitted intensity is collected with the help of photo energy meter.

3. Numerical expression

The present paper deeply rooted through the process of the numerical simulations which depend on the several types of losses to estimate the amount of pressure associated with it. These losses, as stated before are exemplified in terms of reflection, absorption, dispersion, diffraction, polarisation, propagation, scattering, and radiation respectively.

The absorption loss can be expressed in term of absorption coefficient as

$$A = e^{-(2l1\beta1 + l2\beta2)} \tag{1}$$

where, β1, β2 be the absorption coefficient of odd and even layer respectively. Similarly, l1 and l2 are considered to *e* thickness of odd and even layers of the photonic structure respectively.

Similarly, the reflectance can be determined with the help of Helmholtz equation which is given by

$$\frac{d^2 E_z}{dx^2} + \frac{\omega^2}{c^2} E_z = 0 \qquad (2)$$

The solution of equation would be

$$E_z(x,t) = E_0 e^{i(k.x - \omega t)} \qquad 3(a)$$

Further using the proper boundary condition, the electric field intensity can be determined. Finally the reflectance can be written as

$$R = 1 - |E_z|^2 \qquad 3(b)$$

Similarly, the diffraction loss can be expressed as

$$D_{dif} = sin^2(\frac{\pi dn}{\lambda}) \qquad (4)$$

where 'd' represents the total thickness of the proposed one dimensional structure, 'n' defines the refractive index of material with respect to pressure at the signal of 1550 nm (wavelength λ).

Further we move to calculate the polarisation loss efficiency as

$$P_{pol=} \frac{N_0}{N_0 + \frac{2n}{n^2 - 1}} \qquad (5)$$

N_0 be the total number of layers in the structures. Aside these, the equation (6), (7), (8) and (9) represent losses corresponding to scattering, dispersion, propagation and radiation respectively.

The equation of Rayleigh scattering is given below

$$S_{sca=} \frac{8\pi^3}{3\lambda^4} n^8 p^2 LK\beta_C T_F \qquad (6)$$

where λ be the operating wavelength, n is the refractive index, p is average photo elastic coefficient, β_C is the isothermal compressibility of fictive temperature, T_F is fictive temperature, L is the waveguide length.

Modal dispersion loss can be expressed as

$$D_{dis} = \frac{nL}{C} \left(\frac{\Delta}{1 - \Delta}\right) \qquad (7)$$

where n is the refractive index, L is the waveguide length, c is the velocity of light, Δ is the fractional refractive index.

The expression of propagation loss can be written as

$$P_{pro} = e^{\frac{-4\pi na}{\lambda}} \qquad (8)$$

where λ is the input wave length, n is the refractive index, a is the lattice constant.

Similarly expression for radiation loss is [15]

$$R_{Rad} = \frac{4p^2\pi^5 n}{3\lambda^4 \varepsilon_0} c\, pL^2 b^2 n \qquad (9)$$

where p is the power of input signal, c is speed light, λ is the operating wavelength, ε_0 is the permittivity vacuum, L is the waveguide length, b is breadth of structure, n is the medium of index and $n = [1 - \cos\left(\sin^{-1}\left(\frac{n_2}{n_1 + n_2}\right)\right)]$. Where, n_1 and n_2 be the refractive indices of odd and even layer respectively.

Finally, the transmitted intensity is computed corresponding to various losses by using the following expression as

Transmitted intensity= transmitted efficiency × input signal
(10)

where transmitted efficiency = (1-A) × (1-R) × (1-R_{rad}) × (1-D_{dis}) × (1-D_{dif}) × (1-P_{pro}) × (1-P_{pol}) × (1-S_{sca})
(11)

where A, R, R_{rad}, D_{dis}, D_{dif}, P_{pro}, P_{pol}, S_{sca} are absorption, reflection, radiation, dispersion, diffraction, propagation, polarisation and scattering losses respectively. After computing the output result, we move to calculate the sensitivity as

$$S = \frac{\delta I}{\delta P} \qquad (12)$$

I is the output intensity for the photonic structure, δI is the change intensity and δP be the shifting pressure.

4. Result and interpretation

Since the present paper focuses on various numerical investigations pertaining to different losses, let us discuss one by one as follows

4.1. Absorption loss

From equation (1), it is found that the absorbance depends on both absorption coefficient and thickness of odd and even layer of proposed one dimensional photonic structure. The absorption coefficient relies on imaginary part of refractive index of the odd and even layer as

$$\beta 1 = \frac{4\pi n_{impart}}{\lambda_{imput}} \qquad (13)$$

Here, the n_{impart} would be found from the structure at the signal of 1550 nm [16]. Putting the values of n_{impart} and λ_{imput} in the above said equation and

subsequently putting in the equation (1), it is found that the zero loss is associated with the photonic structure at the signal of 1550 nm.

4.2. Reflection loss

Reflection loss of germanium-based one dimensional photonic structure with respect to pressure (0 GPa-10 GPa) is calculated by using plane wave expansion (PWE) method for different waveguide lengths. Further, reflected energy of the structure relies on the length of odd and even layer at the signal of 1550 nm. Aside from this, it depends on refractive indices of germanium material at 1550 nm (Table 1).

Table 1. Refractive indices of germanium with respect to pressure

pressure	0	1	2	3	4	5	6	7	8	9	10
RI	3.99	3.95	3.905	3.87	3.83	3.81	3.775	3.76	3.735	3.725	3.7

Using data from Table 1 and with the help of plane wave expansion method, simulation is done to find the reflectance corresponding to each pressure for all type of waveguides. Though simulations have been done for different lengths and pressure (0 to 10 GPa), the result for 30 nm (length) and 0 GPa (pressure) is indicated in the Fig. 2. Here, the computed result shows that the reflectance is 0.2552 for zero pressure at the signal of 1550 nm.
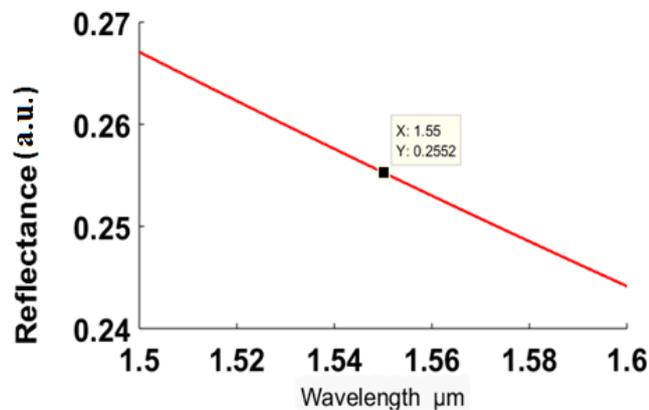
Fig. 2. Reflectance curve germanium of waveguide length 30 nm at wavelength 1550 nm

Similarly, the results for other pressures and different lengths have been computed. The same values of reflectance with respect to the pressure for all chosen lengths have shown through the graphical representation, which is indicated in the Fig. 3.
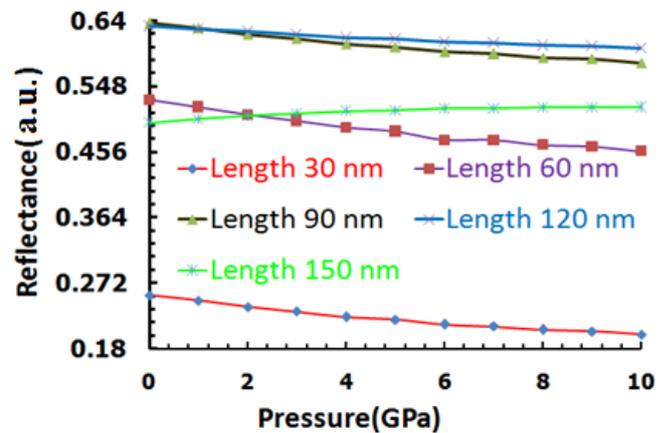
Fig. 3. Deviation of reflectance with respect to pressure for germanium photonic structure (color online)

In the Fig. 3, pressure (GPa) is chosen horizontal axis, reflectance (a.u.) is along the vertical axis. From this figure it is indicated that reflectance decreases with the increasing of pressure except for length 150 nm. For example, the reflectance decreases from 0.2552 to 0.2001, 0.5283 to 0.4566, 0.6361 to 0.5808 and 0.6318 to 0.6009 for length 30 nm, 60 nm, 90 nm and 120 nm respectively. However, the reflectance increases from 0.4969 to 0.5189 for the waveguide length of 150 nm.

4.3. Diffraction and polarisation

Similarly, the diffraction and polarisation loss are computed for all length of 30 nm, 60 nm, 90 nm, 120 nm and 150 nm of photonic structure using the equation (4) and (5) respectively. The same variation is placed in the Fig. 4.
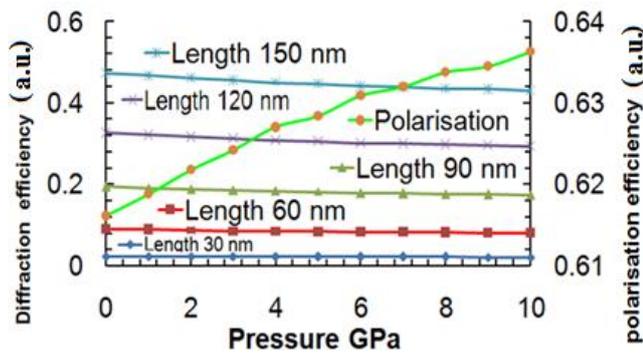
Fig. 4. Deviation of diffraction efficiency and polarisation efficiency with pressure for photonic germanium (color online)

In the Fig. 4, diffraction and polarisation are taken along the primary and secondary vertical axis, where pressure is chosen along horizontal axis. From the graph, it is found that diffraction loss is feeble and it decreases from 0.0228 to 0.0203, 0.0893 to 0.0795, 0.1932 to 0.1728 and 0.3252 to 0.2926 and 0.4732 to 0.4293 for length of 30 nm, 60 nm, 90 nm, 120 nm and 150 nm respectively, however definite amount of polarisation loss is accomplished with the structure at the wavelength of 1550 nm. For example, polarisation efficiency increases from 0.6161 to 0.6363 with respect to the increase of pressure (0 GPa-10 GPa), which shows a linear variation.

4.4. Scattering loss

Basically, scattering loss of germanium photonic structure depends on operating wavelength, refractive index, average photo elastic coefficient, isothermal compressibility of fictive temperature, fictive temperature and waveguide length (equation 6). As far as computation is concerned, the refractive of germanium is found from the reference [6], the average photo elastic constant [17], and compressibility [18] at the signal of 1550 nm. Using above said information, the scattering loss is calculated, and depicted in Fig. 5.
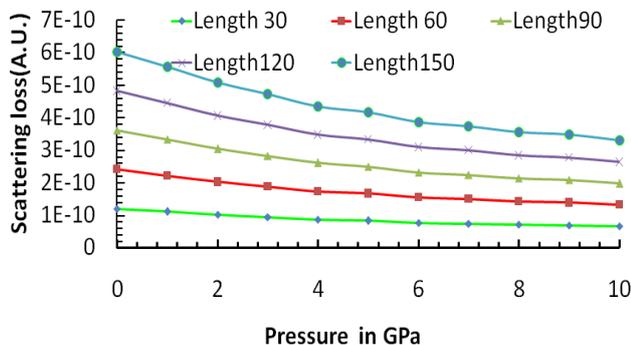
Fig. 5. Scattering losses with respect to pressure (color online)

From Fig. 5, a peculiar result is found for the variation of scattering loss with respect to the pressure. For example, hardly scattering loss is found for all type of length with respect to the pressure from 0 GPa to 10 GPa at the signal of 1550 nm. Further, there is a minute variation observation that indicates the scattering loss varies from 1.206×10^{-10} to 6.594×10^{-11}, 2.412×10^{-10} to 1.319×10^{-10}, 3.618×10^{-10} to 1.978×10^{-10}, 4.824×10^{-10} to 2.637×10^{-10} and 6.029×10^{-10} to 3.297×10^{-10} for the waveguide length of 30 nm, 60 nm, 90 nm, 120 nm and 150 nm at the signal of 1550 nm respectively.

4.5. Dispersion loss

Basically, intramodal dispersion is associated with the proposed one dimensional photonic structure as we have considered a single wavelength impinging to the structure. Such dispersion relies on the refractive index of structure. The same dependence parameter is indicated in the equation (7); the output result is shown in the figure.
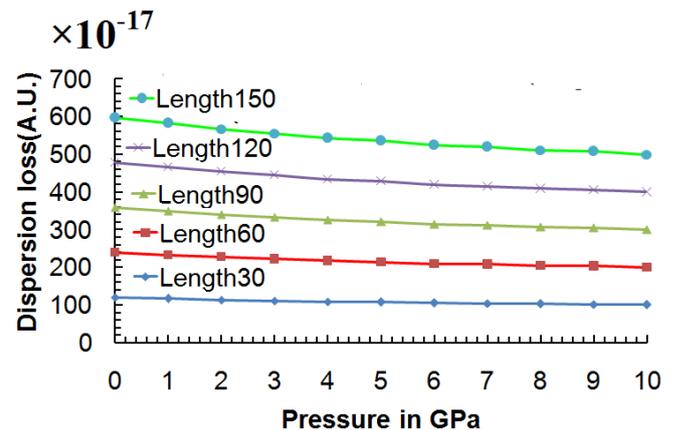
Fig. 6. Pressure versus dispersion loss diagram (color online)

In Fig. 6 dispersion decreases with the increasing of pressure. Moreover, it indicates that the squeeze structure gives less dispersion. It is also found that the structure will have more dispersion, if the length is more. For example, dispersion loss varies from 119.3007×10^{-17} to 99.9001×10^{-17}, 238.601×10^{-17} to 199.8003×10^{-17}, 357.9022×10^{-17} to 299.7004×10^{-17}, 477.2029×10^{-17} to 399.6005×10^{-17} and 596.5036×10^{-17} to 499.5007×10^{-17} for the waveguide length of 30 nm, 60 nm, 90 nm, 120 nm and 150 nm respectively.

4.6. Propagation loss

The propagation loss factor depends on the equation (8), which relies on real part of refractive index of odd and even layer, lattice constant of structure and input signal. After substituting the values of aforementioned

parameters, the variation of propagation loss with respect to pressure for all lengths are viewed and indicated in the Fig. 7.
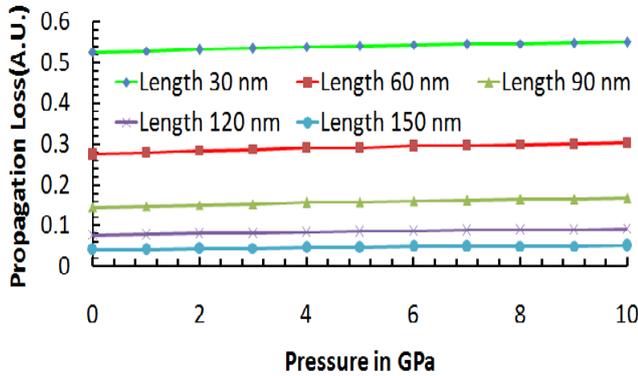
*Fig. 7. Pressure versus propagation loss diagram
(color online)*

From Fig. 7, even though the propagation loss seems to be constant for a particular length but it increases with small increment for all waveguide lengths. For example, propagation loss varies from 0.524 to 0.549, 0.274 to 0.301, 0.144 to 0.165, 0.0753 to 0.0908 and 0.0394 to 0.0499 for the waveguide length of 30 nm, 60 nm, 90 nm, 120 nm and 150 nm respectively

4.7. Radiation loss

Primarily the radiation loss depends on input signals, the effective indices of proposed structure, input power, configuration of structure, along with the nature of material. The same relation is found from the equation (9). Putting the proper information in the same equation, radiation loss is found with respect to pressure for different lengths, which is indicated in Fig. 8.
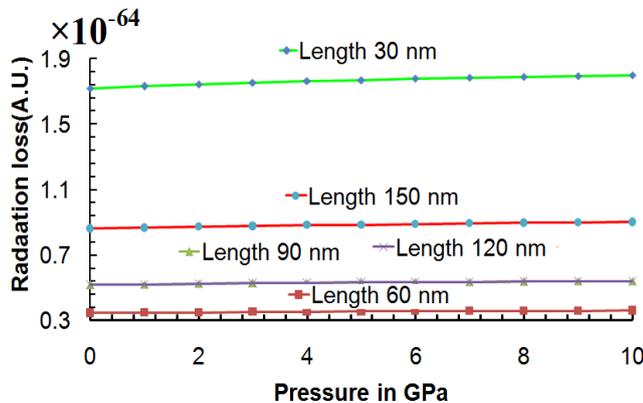
*Fig. 8. Pressure versus Radiation loss diagram
(color online)*

In Fig. 8, radiation loss and pressure are taken along vertical and horizontal axis respectively. In this result, radiation loss varies from 1.7198×10^{-64} to 1.8000×10^{-64}, 0.344×10^{-64} to 0.360×10^{-64}, $0.5162634 \times 10^{-64}$ to $0.5403544 \times 10^{-64}$, $0.51626343 \times 10^{-64}$ to $0.54035438 \times 10^{-64}$ and 0.860439×10^{-64} to 0.900591×10^{-64} for the waveguide length of 30 nm, 60 nm, 90 nm, 120 nm and 150 nm respectively. From above result, it is observed that the radiation loss in null for all pressure.

4.8. Computation of transmitted intensity

Finally, transmitted intensity at the output end (Fig. 1) can be determined using the formula (10). The output result corresponding to all chosen lengths are indicated in the Fig. 9.
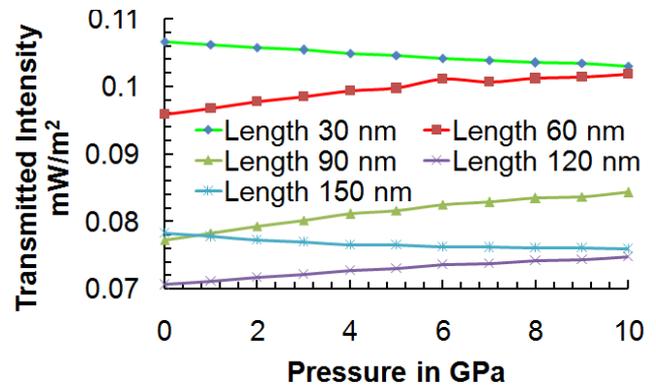
*Fig. 9. Pressure versus Transmitted intensity of germanium
(color online)*

In the Fig. 9, the pressure in GPa and transmitted intensity mW/m^2 is taken along horizontal and vertical axis respectively. It is realised that pressure in GPa increases with respect to transmitted intensity mW/m^2 for all lengths of photonic structure. For example, transmitted intensity varies from 0.10655 mW/m^2 to 0.102936 mW/m^2, 0.09583 mW/m^2 to 0.101774 mW/m^2, 0.077288 mW/m^2 to 0.084283 mW/m^2, 0.070634 mW/m^2 to 0.074757 mW/m^2 and 0.078286 mW/m^2 to 0.075979 mW/m^2 for the waveguide length of 30 nm, 60 nm, 90 nm, 120 nm and 150 nm respectively. From above said result, it is inferred that the amount of pressure in the photonic structure can be determined by knowing the output intensity.

4.9. Sensitivity

Finally, we move to compute the sensitivity of measurement of pressure corresponding to the all lengths. The same computation can be understood from the equation (12) and the final result can be found, which is indicated in the Fig. 10.
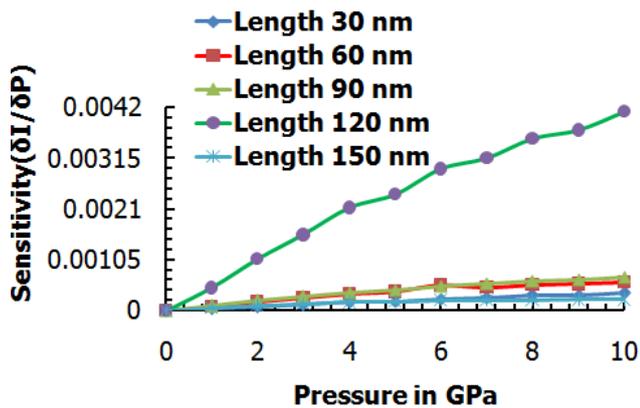
Fig. 10. Pressure versus sensitivity (color online)

In this figure, sensitivity and pressure are taken along vertical axis and horizontal axis respectively. Here, it is observed that sensitivity differs from different lengths. It varies from 3.88×10^{-05} to 0.0003614, 8.72×10^{-05} to 0.0005944, 9.24×10^{-05} to 0.0006995, 0.000471 to 0.004123 and 5.37×10^{-05} to 0.0002287 for the waveguide length of 30 nm, 60 nm, 90 nm, 120 nm and 150 nm respectively. After analysing the above said results, it is realised that the computational result is accurate and device would be quick to detect the amount of pressure. However, the minimum and maximum sensitivity are 0.0002287 and 0.00924 respectively.

5. Conclusion

The amount of pressure associated with germanium material is meticulously investigated through one dimensional photonic structure. The operational mechanism deals with the different types of losses (absorption, diffraction, dispersion, reflection, radiation, propagation, polarisation and scattering) to accomplish the same. In this research, the sensitivity factor is calculated through pressure variation which shows an excellent result pertaining to the current research scenario. Finally, it is revealed that, the amount of pressure in germanium crystal is computed from the knowledge of transmitted intensities at output end. In conclusion, this work could be a stepping stone towards advanced research in the field of photonics.

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