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Simulation Study of Strains Obtained by Two Different Scattering Processes in Optical Fiber Sensors

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Abstract- Distributed Sensing plays a key role in the realm of modern sensing technology and fiber optic sensors are the ultimate choice for that. Fiber optic distributed sensors are extremely popular because it can able to measure strain and temperature difference with very high resolution of about 2 cm. In this paper we have tried to simulate the process of measuring the strains using Stimulated Brillouin and Rayleigh scattering by FDTD method and tried to investigate how well it will match with the strains obtained from the experimental process. These distributed sensors are used to monitor mainly the structural health of the civil or mechanical engineering systems and are facilitate to develop advanced sensing devices like Distributed Acoustic Sensors.

Keywords: Stimulated Brillouin Scattering, Rayleigh scattering, FDTD, Optical Fiber Sensor, Cross-correlation, Tunable Wavelength Coherence Time Domain Reflectometer (TW-COTDR)

I. Introduction

Till date a lot of work has been done in the field of distributed strain and temperature sensing using fiber optic sensor. There are no other sensing devices except the fiber optic sensors which can measure minute changes in strain and temperature for a long distance of few kilometers effectively and efficiently. Modeling of fiber optic sensors and simulating through Numerical Analysis like FDTD need lot of innovative ideas and have to overcome lot of challenges. The challenges are of two fold. Firstly, we cannot model a large structure because it requires lot of memory and time. Secondly, in the case of Rayleigh scattering the grid size should be less than the scatterer size. Now in case of Rayleigh scattering the scatterer size is more or less has the dimension of a molecule so it is nearly impossible to model it. So we have tried to make an approximate model of both the scattering which give an idea of internal optical processes when applied to strain to it. As mentioned earlier, mainly two types of scattering in which we are interested upon, Stimulated Brillouin Scattering and Rayleigh scattering. When energy is coupled between counter propagating acoustic waves and the light waves Stimulated Brillouin scattering is occurred [1]. An incident beam of field strength E_{in} is launched from a laser source to an optical fiber with center frequency ω_L generates a refractive index variation, which in turn gives rise to a sound wave of field strength ρ of frequency Ω. The sound wave fades away from the incident source, therefore it produces a backscattered wave of field strength E_s. It is quite obvious that the frequency of the backscattered wave denoted by ω_S is $\omega_L - \Omega$. This backscattered wave is nothing but the Stokes wave, which interacts with the laser source supports production of the sound waves, equally the interference of the laser wave with sound waves strengthens the Stokes wave. If a positive feedback is introduced in between two intergeneration processes the exponential growth of the Stokes wave can be observed, thus Stimulated Brillouin scattering is achieved [2].Acoustic wave is captured is described by the pressure wave with local pressure variation parameter Δp given as[5]

$$\frac{\partial^2 \Delta p}{\partial t^2} - \Gamma \nabla^2 \frac{\partial \Delta p}{\partial t} - \mathrm{v}_a^2 \nabla^2 \Delta p = 0 \qquad (1)$$

where, Γ is the damping parameter and v_a is the sound velocity in the medium. The corresponding difference equation is

$$\Delta p(x, t+\Delta t) = -\Delta p(x, t-\Delta t) + 2\Delta p(x,t) + \frac{\Delta t^2}{h^2}\{\mathrm{v}_a{}^2 + \frac{\Gamma}{h}[\Delta p(x, t+\frac{\Delta t}{2}) - \Delta p(x, t-\frac{\Delta t}{2})]\} d_x^2 \Delta p(x,t)$$

(2)

where, Δt is the time step and h is the space step, generally taken to as 1. Now we iterate the equation (2) mentioned above to get the desired result.

Rayleigh scattering is a very complex electromagnetic process where the wavelength of the incident light has very high order of dimension than that of scatterer size. If we denote the wavelength of the incident by "λ" and the radius of the scatterer by "a" , then the criterion for the Rayleigh scattering is $\lambda >> a$. So basically it is molecular process where the light is interacted to the electric fields of the molecules of the material. Also inside an optical fiber which is made of glass, light interacts with the fields of molecules of glass which is innumerable in number. So for the measurement of strain by means of optical fiber is tremendous complicated process using Finite Difference Time Domain (FDTD) because of mainly two reasons. First of them, we just cannot increase infinitely the number of molecules because it also increase the memory requirements and run time infinitely and the next one is interaction of light to the peripheral electron clouds of the innumerous molecules is very difficult to accomplish. Rayleigh scattering based distributed sensors are the best choice among others [3, 4] due to its high accuracy. With the help of this technique one can measure complex Rayleigh backscatter signatures with a sampling interval of one cm and spatial resolution 2 cm. When electromagnetic field is applied to the molecules of the materials by which any specimen is constructed, it alters the macroscopic charge neutrality. In order to reinstate that it persistently undergoes modification of electron clouds. When light falls on the specimen, the molecular electrons start to vibrate in unison and by this development it increase the coherence of the randomly oscillating electron clouds. As the permittivity of any material is dependent on the charge contain of it, so for the sake of maintaining the charge neutrality, the permittivity of the specimen is constantly being adjusted with time and distance. This external electric field E gives rise to frequency dependent Polarization P , which is inter related by the equation $P = \varepsilon_0 \chi E$, where χ is the material susceptibility. The changing permittivity gives rise to polarization induced light emissions in all directions [5]. Now some of the backscattered light is collected by the optical fiber and is use for distributed sensing. Permittivity, $\tilde{\varepsilon}(\boldsymbol{x},\omega)$ has frequency independent and frequency-dependent parts in the form

$$\tilde{\varepsilon}(\boldsymbol{x},\omega) = \varepsilon_1(\boldsymbol{x}) + \tilde{\chi}(\boldsymbol{x},\omega) \quad (3)$$

where, ε_1 is frequency independent component and $\tilde{\chi}$ holds the frequency-dependent part of $\tilde{\varepsilon}$. So the Maxwell's Equation for wave propagation becomes,

$$E(x,t+\Delta t) = \frac{1}{\varepsilon_1(x) + \bar{\chi}(x,0)}\left[\varepsilon_1(x)E(x,t) + d \times H(x,t+\Delta t/2) - \Psi(x,t)\right] \quad (4)$$

where, d is the difference operator .Here, $\bar{\chi}(\boldsymbol{x},t)/\Delta t$ is the time average of $\chi(\boldsymbol{x},t)$ at the time interval of t to $t+\Delta t$. $\chi(\boldsymbol{x},t)$ and $\tilde{\chi}(\boldsymbol{x},\omega)$ are the Fourier Transform pair.

Here, Ψ is the "accumulation field vector" [6] and can be calculated by repetitions,

$$\Psi(x,t+\Delta t) = \Delta\chi(x,0)E(x,t+\Delta t) + \zeta\Psi(x,t) \quad (5)$$

where, $\zeta = e^{-\Delta t/\tau}$ and τ is a constant.

Now, iterating the equation (4), one can get the Rayleigh scattered field in all directions but we are only interested in the backscattered field. In order to get the values of strains from the experimental values, the formulas which combine the Strain and Temperature in room temperature (25^0C) are [8, 9]:

$$\Delta\nu_B = C_{11}\Delta\in + C_{12}\Delta T \quad (6)$$

$$\Delta\nu_R = R_{11}\Delta\in + R_{12}\Delta T \quad (7)$$

where ,

$\Delta\in$: strain change

ΔT : temp change

$\Delta\nu_B$: frequency shifts in Brillouin scattering

$\Delta\nu_R$: frequency shifts in Rayleigh scattering

$C_{11}\&R_{11}$: frequency -strain coeffs

$C_{12}\&R_{12}$: frequency-temp coeffs

In order to find Coefficients C_{11} and R_{11}, while calibration of an unknown optical fiber, one should change the strain of the test fiber in an isothermal condition that means there is no temperature change or $\Delta T = 0$ and observe $\Delta\nu_B$ and $\Delta\nu_R$. Then from the equations (6) and (7) one can get

$$C_{11} = \Delta\nu_B / \Delta\in \quad (8)$$

and $R_{11} = \Delta \nu_R / \Delta \in$ (9)

where, $R_{11} = -0.15269\text{GHz}/\mu S$. From the equation (9) we can calculate the value of difference in strain $(\Delta \in)$, when the Rayleigh frequency shift is known.

II. FDTD Modeling and Discussions

Here, we have mimicked the situation of optical fiber sensors laying on the steel specimen subjected to various amounts of increasing stress applied to it. Initially, at stress free condition the optical fiber has only one section, having the core diameter of 4.5 μm with refractive index (r.i) of 1.49 and cladding with 1.48 (r.i) of diameter 9 μm. The total length of fiber is 8 μm, in which the effective length of the fiber area where actually the stress is translated into strain is the 2 μm of the middle section of it. A FDTD Solutions 7.5 solver (Lumerical) 3D simulator has been taken for the simulation for all the models mentioned in the article.

When it is applied to stress, the single strand of the fiber sensor can be modeled into three different parts as described in the next paragraph.

Starting with the middle portion of the single mode fiber which has 3.6 μm diameter with refractive index (r.i.) 1.49 and cladding of9 μm diameter with r.i. 1.48. At the top, there is another single mode fiber attached firmly to it of core 4.5 μm diameter with r.i.1.48, and cladding of 9 μm diameters with r.i.1.48. Similarly, at the bottom, there is also another fiber attached firmly with a core diameter of 4.5 μm with r.i. of 1.48 and cladding of 9 μm diameter with r.i. of 1.48.Upper and lower part of the fiber has the length of 2 μm, and the middle portion has the length of 4 μm, so the total length of the fiber is 8 μm. Supposing the effective part of the fiber where the stress actually has the effect by developing strain into it is the middle part and of length 4 μm, when we gradually increase the stress, the length of the middle section gradually increased. The perspective view of the fiber optic sensor is shown in figure 1 as below.

From the figure 1 one can observe easily, two blue colored columns in which the inner one (brighter one) is the core and the lighter one is the cladding of the fiber. Figure 1 (a) indicates that the core column and the cladding column is uniform as it is the necessary condition for stress free sensor. In this case is no change in the shape. Whereas, in figure 1 (b), one can easily see the core in the middle section is altered when the stress is applied. In fact, the entire fiber of the middle section including core and clad suffers the deformation, but as the light propagates through only core, the deformation in the cladding has no significant role in light propagation. So in order to make the model a simple, we haven't change the clad diameter. At first, no scatterers have been introduced, but they are introduced later in order to simulate this model for strain calculation by Rayleigh scattering method. The violet colored arrow is the light source as depicted in figure 1. The red colored box is the computational space and the yellow colored box is the mesh.

(a)

(b)

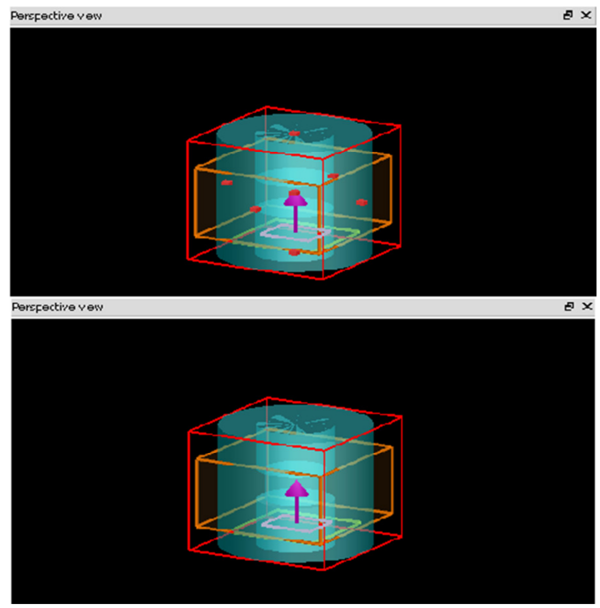

Fig.1.Perspective view of the optical fiber sensor
(a) Without stress condition and
(b) With stress condition

In this paragraph we shall discuss the profile of the light source used in this simulation, which is shown by figure 2. The injection axis of the light is "z" and is in the forward direction which is directed upward. The normalized amplitude of the source has been taken as 1 for this simulation. The mode of the source has been taken as fundamental mode because it renders stability and electromagnetic energy is maximum while propagating through the optical fiber. Here, the frequency range of the source is taken as 194THz~194.3THz. The pulse length is estimated to be 10.1916 femto seconds and the bandwidth is calculated as to 43.2975 THz.

Just below the source we have placed a monitor to detect the backscattered Rayleigh signal. It is a data recorder with Standard Fourier Transformation. The frequency points that it can measure are 20000 and it has the same range of frequency detection of that of light source i.e. 194THz~194.3THz. Now we have been introduced 10000 scatterers inside the model in the area of our interest, described in the following section.

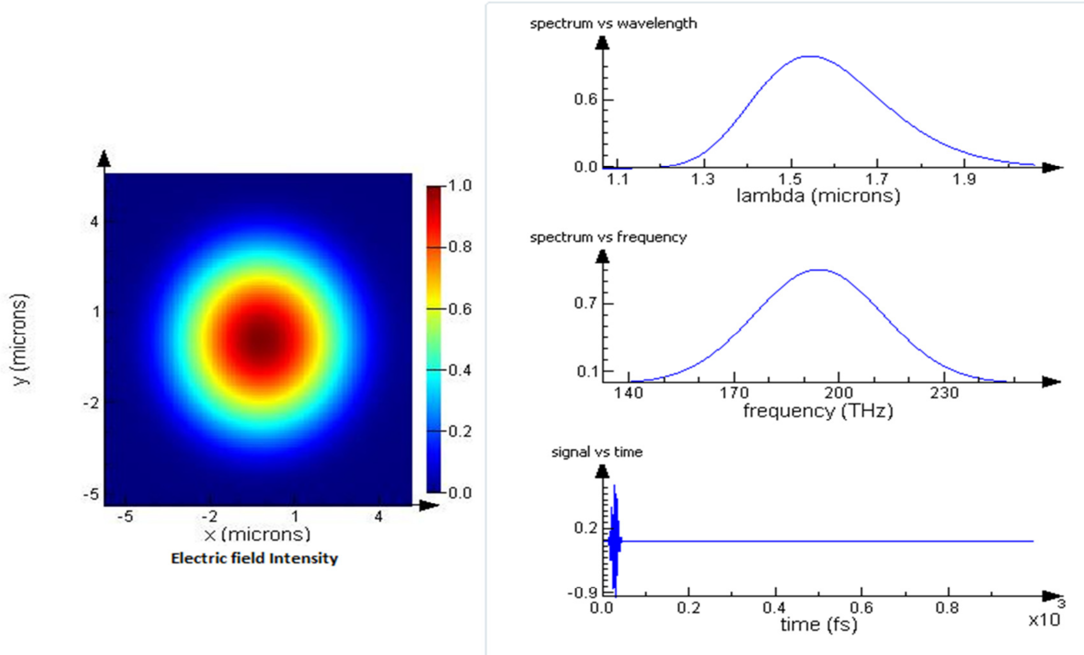

Fig.2. Source Profile

III. SBS Model

For Stimulated Brillouin Scattering (SBS) inside the Optical fiber we have taken two sources instead of one inside the fiber model as shown in figure 3. Here, the source which supplies the amplification is known as Pump (bottom one in the figure 3), whereas the other one which carries the actual strain signals known as probe. The pump signal has the characteristics, also seen in earlier case; the frequency range is in between 194THz~194.3THz. The pulse length is estimated to be 10.1916 femto seconds and the bandwidth is calculated as to 43.2975 THz. It corresponds to the wavelength range from 1.544~1.546 micrometer. The probe has the wavelength of that visible light range of 400~700 nanometer. The other parameters remain same as before. Both the sources are mode sources and maintain its fundamental modes throughout the simulations.

Now, for the experiment the mechanism goes like this. As shown in figure 3, we have three sections of the fiber, the upper and the lower sections which have the length 2 μm each, do not undergo any change in length when subjected to stress. Only the middle portion of 4 μm undergoes changes in a linear fashion with stress. It obeys the simple relation of stress to length changes given by

$$0\text{MPa} \rightarrow 4\mu m;$$
$$40\text{MPa} \rightarrow 4.2\mu m; 80\text{MPa} \rightarrow 4.4\mu m; 120\text{MPa} \rightarrow 4.6\mu m;$$
$$160\text{MPa} \rightarrow 4.8\mu m; \text{and } 200\text{MPa} \rightarrow 5\mu m.$$

The refractive index of core is taken to be 1.49 and that of clad 1.48 and we introduce Kerr nonlinear $\chi(2)$ into the material.

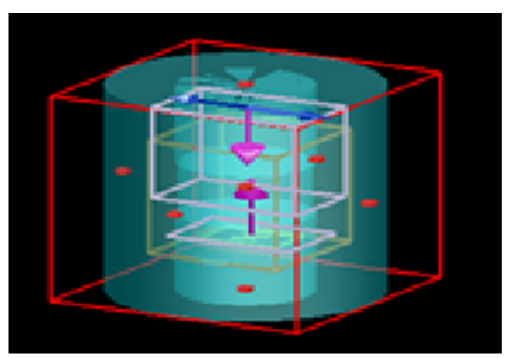

Fig.3. Model for SBS Simulation

Here also, just below the source we have placed a monitor to detect the backscattered SBS signal. It is a data recorder with Standard Fourier Transformation. The backscattered SBS spectrum is shown in figure 4.

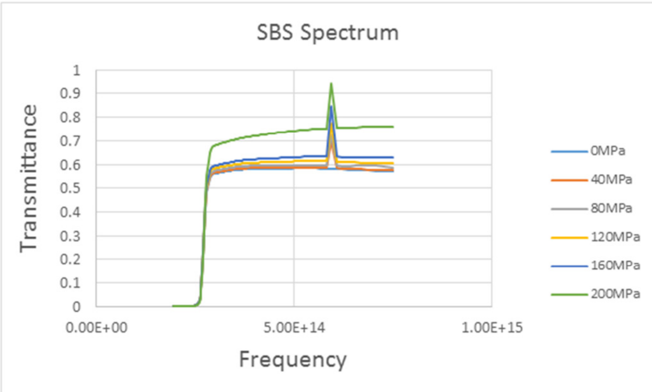

Fig.4. Transmittance vs frequency of SBS backscattered Spectrum

From the figure 4 it is clearly seen at a frequency of 5.9467×10^{14} Hz. There is a clear change of increasing amplitudes of transmittance as we increased the applied stresses in the fiber. This is due to the fact as we increased the stress, the generation of pressure waves are more. Now more number of pressure waves interacts with the light waves and generate backscattered Stokes waves which is being detected by the detector. Increased in stress also increase the strain in the optical fiber. So there is a one to one relationship with change in transmittances with strains when the stresses are changed. The stress to transmittance correspondence goes like this: $0\text{MPa} \rightarrow 0.581; 40\text{MPa} \rightarrow 0.696$; $80\text{MPa} \rightarrow 0.723$; $120\text{MPa} \rightarrow 0.773$; $160\text{MPa} \rightarrow 0.846$ and $200\text{MPa} \rightarrow 0.942$. Initially we set the reference at 0MPA having the corresponding strain to be 0 μS . As we know the transmittance has direct correspondence with the strain therefore differences in the transmittance will give the scale down version of differences in strain. If we estimate an appropriate scaling factor and multiplying that we will get the absolute strains shown by Table 1. From the graph depicted by figure 5, the scaling factor is estimated as 1000.

Table 1.

Serial No.	Tensile Stress applied to the specimen (MPa)	Difference in Transmittance	Strain = {(Difference in Transmittance)* 1000} (Expressed in μS and is obtained from Simulation of FOS)	Strain (From the experiment expressed in μS)
1	0	0	0	0
2	40	0.015	150	182
3	80	0.027	270	348
4	120	0.050	500	510
5	160	0.073	730	680
6	200	0.096	960	850

In the graphical form it is shown in figure 5.

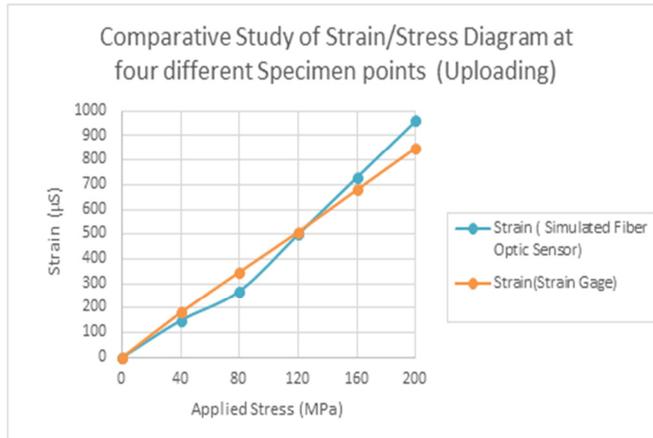

Fig.5. Comparisons of Strains by Fiber Optic Sensor (Simulation) and Strain gage

From the figure 5, we have understood the strains measured from Stimulated Brillouin scattering using fiber optic sensors are not accurate at the high stress levels.

IV. 10,000 Scatterer Model (for Rayleigh scattering):

In order to observe the effect of Rayleigh scattering we have introduced 10000 scatterers, each of having average diameter of 0.075 μm in our model and is distributed up to the cladding region as shown in figure6.In the "z" direction we have deliberately distributed the scatterers on the both side of the center position of the model of a span of 4.5 μm , covering our middle part of active area 4 μm . Scatterers outside the effective zone have no significant effects on this active middle area and would contribute nothing for Rayleigh scattering. Covering the entire region of the fiber would increase unnecessary computational time and memory.

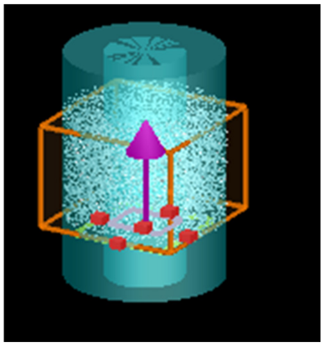

Fig.6. Perspective view of the optical fiber sensor in strained condition with 10,000 scatterers in the zone of interest

As the scatterers are distributed in core and cladding regions, the refractive index of the scatterers are taken intermediate to the refractive index of both the regions i.e. 1.485.

In this section we are going to discuss the procedure of conducting the simulation process in analogy to the experiment conducted above. As stated earlier, we have started with a total of 8 μm length optical fiber sensor with an active region of 4 μm in the middle; this corresponds to no stress or stress free condition of the fiber. Now when we have applied to 40 MPa Stress to the fiber, we have assumed that the effective length of the center region is changed from 4 μm to 4.2 μm , so that the entire length of the fiber changed from 8 μm to 8.2 μm . In other words, 0MPa corresponds to 8 μm of fiber length, which is the initial length of the fiber in our simulation model and 40 MPa corresponds to 8.2 μm . According to this logic we have proceed on and the entire "stress to length of correspondence" which is represented by Table 2.

Table 2.

Serial No.	Applied Stress (MPa)	Length of the fiber in μm for simulation
1	0	8.0
2	40	8.2
3	80	8.4
4	120	8.6
5	160	8.8
6	200	9.0

The refractive index of the back ground (free space) has been taken to be 1. PML is selected as the boundary conditions in all the directions so that there is no refection from the edges. The minimum step size for the computation has been taken as 0.0025 μm .The mesh type is used namely Yu-Mittra (Method 2) and was introduced by Yu and Mittra [10] to provide greater accuracy when modeling with dielectric interfaces.

In this simulation, the light is propagated in the upward direction from the source (indicated by the direction of arrow in figure 6) and the back scattered light is collected by Frequency-domain field monitor which is used to collect steady state reflected Electro-Magnetic field continuous wave data in the frequency domain. We have changed the length of the optical fiber in between 8 μm to 9 μm in steps of 0.2 μm consistent with Table 2 and recorded the corresponding backscattered spectrums as shown in figure 7.Values obtained for 8 μm length is considered as reference data as it corresponds to 0 MPa applied stress. It is to be noted that we have increased the length in linear fashion as the stress is increased in a linear way.

Now we have proposed a new scheme by which we are going to calculate the values of strains from the correlation values. Rayleigh backscattered spectrum values which is derived for the length of 8 μm , always gives the value 1 while taking the correlation with itself, because it manifests into auto-correlation. So, in order to fix the starting point with zero Strain we have simulated one more time this particular model with a compressive strain of 40MPa which compress the optical fiber to a length of 7.8 μm . After getting the back scattered spectrum for the fiber length of 7.8 μm (not shown in figure 7) we have found the cross correlation between the spectral data of 8 μm and 7.8 μm which turns around to be 0.675598.

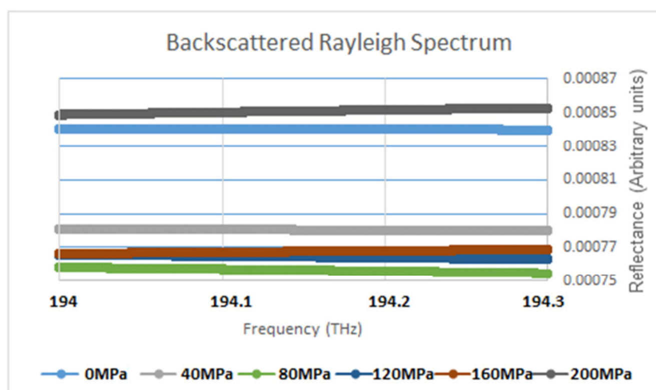

Fig.7. Backscattered Rayleigh spectrum for 10000 scatterers at different applied stress

In this fashion we have continued on and performed cross correlations between the two successive spectrums, whose values are shown in Table 3. We have also found the mod values of difference of the absolute values of two successive cross correlations displayed in this table. In this context, we have proposed that difference of the cross correlation values yields the change in strain values exactly in the same manner. So by multiplying the mod values with 100 provide us the changed value of strain in percentage.

Table 3.

Serial No.	Fiber lengths in μm for which correlation values of their spectrum will be calculated		Correlation values of their spectrums (r_{xy})	Mod values of the difference of the absolute values of two successive cross correlation values $\lVert (r_{x,y}) \rvert - \lvert (r_{x-1,y-1}) \rVert$	Changed value of Strain in percenta -ge (%)
	x	y			
1	7.8	8	0.675598	Not defined	0%
2	8	8.2	0.718946	0.04335	4%
3	8.2	8.4	0.997666	0.27872	27%
4	8.4	8.6	0.999987	0.00232	0%
5	8.6	8.8	-0.99851	0.001478	0%
6	8.8	9.0	0.999833	0.001324	0%

Now taking the initial value of strain as 156.67 μS from the experiment using fiber optic sensor and fitting it in our model, the successive strains has been calculated accordingly, shown in the last column in Table 4.

Table 4.

Serial No.	Tensile Stress applied to the specimen (MPa)	Corresponding Fiber lengths (μm)	Measured Strain (μS) (from Fiber Optic Sensor)	Strain (μS) from our calculation
1	0	8	0	0
2	40	8.2	156.67	162.93
3	80	8.4	305	369.85
4	120	8.6	455	576.77
5	160	8.8	608.33	783.69
6	200	9.0	759.997	990.61

The comparison of the strains obtained from the experiment with optical fiber sensor and from the simulated optical fiber sensor is shown in figure 8 below. It is noticed that they did not match very well. This is due to the reason 10000 scatterers are not sufficient to get an accurate backscattered spectrum. So in the next model we have increased the number of scatterers to 20000.

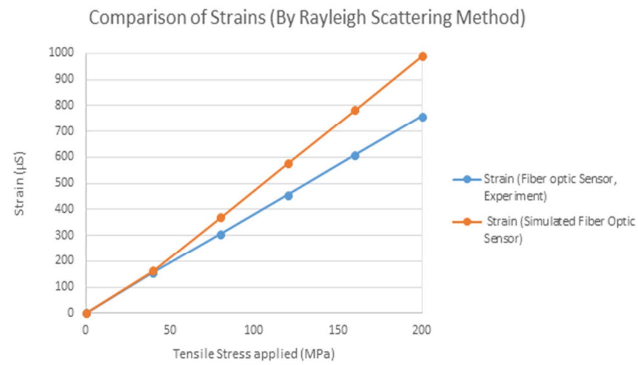

Fig.8. Comparisons of Strains by Fiber Optic Sensor (Experimental) and Simulated Fiber Optic Sensor

V. 20,000 Scatterer Model (for Rayleigh scattering):

We have extended our model to 20000 scatterers and have tried to analyze stress - strain relationship based on backscattered Rayleigh spectrum. All the other parameters apart from the number of scatterers are remained same. Increased number of scatterers will provide better Rayleigh back scattering therefore the spectrum becomes more accurate. Similar to 10000 scatterer model, we have started with a total 8 μm length optical fiber sensor with an active region of 4 μm in the middle. This corresponds to no stress or stress free condition of the fiber. Now when we have applied 40 MPa Stress to the fiber, so the effective length of the center region is changed from 4 μm to 4.2 μm. Therefore the entire length of the fiber changed from 8 μm to 8.2 μm. Similar to the previous model, 0 MPa corresponds to 8 μm of fiber length, which is the initial length of the fiber in our model. 40 MPa corresponds to 8.2 μm of fiber length and this stress to length of correspondence remained same as earlier and is depicted by table 2.

The backscattered Rayleigh spectrum is shown by figure 9.

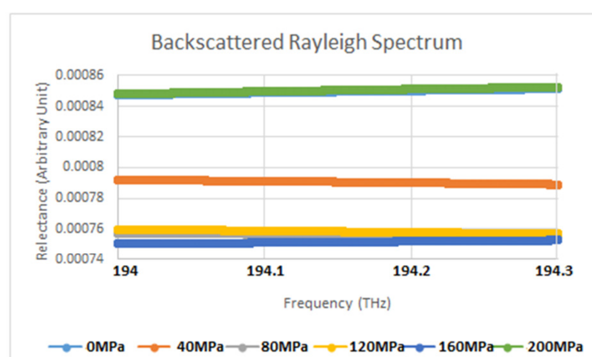

Fig.9. Backscattered Rayleigh spectrum for 20000 scatterers at different applied stress

The relationship between the cross correlation values and the strain values obtained by the Rayleigh spectrum shown in figure 9 is given by Table 5.

Table 5.

Serial No.	Fiber lengths in μm for which correlation values of their spectrum will be calculated		Correlation values of their spectrums (r_{xy})	Mod values of the difference of the absolute values of two successive cross correlation values $\left\|\left|(r_{x,y})\right|-\left|(r_{x-1,y-1})\right|\right\|$	Changed value of Strain in percentage (%)
	x	y			
1	7.8	8	0.999768	Not defined	0%
2	8	8.2	-0.99471	0.04335	0%
3	8.2	8.4	1	0.00529	0%
4	8.4	8.6	0.99943	0.00057	0%
5	8.6	8.8	-0.99906	0.00037	0%
6	8.8	9.0	0.999836	0.000776	0%

Here also, the initial value of strain has been taken as 156.67 μS from the experiment of the fiber optic sensor and after fitting it in our model, successive strains have been calculated accordingly, as shown in the last column in Table 6.

Table 6.

Serial No.	Tensile Stress applied to the specimen (MPa)	Corresponding Fiber lengths (μm)	Measured Strain (μS) (from Fiber Optic Sensor)	Strain (μS) from our calculation
1	0	8	0	0
2	40	8.2	156.67	156.67
3	80	8.4	305	313.34
4	120	8.6	455	470.01
5	160	8.8	608.33	626.68
6	200	9.0	759.997	783.35

The comparison of the strains obtained from the experiment with optical fiber sensor and from the simulated optical fiber sensor shown in figure 10 below. It is noticed that they have matched very well and quite better than the previous case.

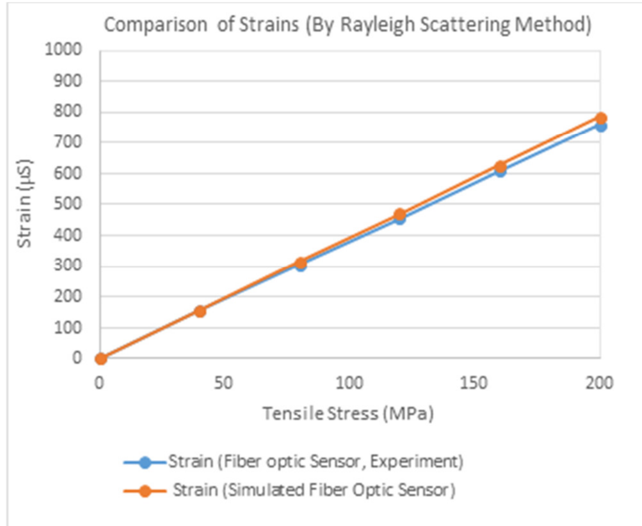

Fig.10. Comparisons of Strains by Fiber Optic Sensor (Experimental) and Simulated Fiber Optic Sensor

VI. Conclusions

We have proposed and applied a new scheme to find the change in the strain values from the Cross correlations of two successive Rayleigh backscattered spectrums obtained from our simulation. Taking that into consideration, we have compared the values of strains obtained from our experiment using fiber optic sensor at a particular location to the calculated values from our simulations. The initial value of strain has been supplied and the other values of strains are calculated accordingly from our method.

In this process we have noticed the 20,000 scatterer model is better than 10,000 scatterer model. More numbers of scatterers, the backscattered spectrums become more correlated. As the strain change values are directly proportional to the mod of the differences of the absolute values of two successive Cross correlations, higher the numbers of scatterers better are the values.

We have also noticed that at higher stress levels starting from 50MPa and onwards the strains measured from Stimulated Brillouin scattering using fiber optic sensors are not accurate. It is because in the high stress levels the fundamental mode of light propagating through the fiber changes and the single mode fiber does not support that.

VII. Acknowledgement

The authors would like to thank all the people of Neubrex Co., Limited Kobe, Japan; who provided us with the support being required for the experiment. We would also like to thank Dr. Hagiwara Masuo (NIMS, Japan) to help us to perform the tensile test and Dr. Dmitry Bulgarevich (NIMS, Japan) to help us to develop the FDTD scatterer model for Fiber Optic Sensor.

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