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Transverse Scattering Characterization of Refractive Index Sensor in Tapered and Untapered Photonic Crystal Fiber (PCF)

S.N. Sanusidin, M. I. Md Ali, and M. H. M.Yusoff

Abstract— **This paper brief about the simulation of transverse scattering of liquid filled tapered and untapered Photonic Crystal Fiber (PCF) to function as a refractive index sensor. The simulation was conducted using Finite Difference Time Domain (FDTD) simulation for a wavelength range of 0.6 to 1.7 µm. The transverse scattering was correlated with the refractive index in the liquid filled PCF. It was investigated for untapered PCF with fiber outer diameter 125 µm and a series of tapered PCF from 90% until 10% of the original size. The transverse spectrum was analyzed using Principal Component Analysis (PCA) and the simulation results showed a correlation between the spectrum and the refractive index of liquid filled PCF. The sensitivity at singlewavelength and multiwavelength is proven to be 7.45 and 4.76 a.u/RIU respectively. The untapered PCF gives the most sensitive configuration for refractive index sensing application.**

Keywords---- tapered, photonic crystal fiber, scattering pattern, transverse transmission spectrum, outer diameter.

I. Introduction

Refractive index (RI) sensors have many prodigious applications in many fields, especially in bio-sensing for monitoring molecular bindings and chemical industry for quality control [1]. Optical fiber based RI sensors are attractive, due to their light weight, immunity to electromegnetic interference, environmental ruggedness, high temperature performance and ability for distributed sensing [1]. The development of fiber grating has produced a significant on research and development in telecommunications and fiber optic sensing. Fiber brag gratings are intrinsic devices that allow the control over the properties of light propagating within the fiber. They are used as spectra filters, as dispersion compensating components, and in wavelength division multiplexing system [2].

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Due to the nonconventional propagation characteristics of photonic crystal fibers (PCFs), the interferometric sensors based on PCFs built via fusion splicing and micro-hole collapsing have been demostrated and are getting more and more attention [3, 4]. This kind of PCF based on in-lined model interferometers (PCFMIs) consist of a stub of 125 µm large-mode-area (LMA) PCF spliced between the same size standard single-mode fibers (SMFs) [1]. Because cladding mode is sensitive to outside environment, it can be uses as a RI sensor to detect the outer region of the PCF. Furthermore, the device are very small because the PCF needed is just a few centimeters long and highly stable over time [1]. PCFs are characterized by a pattern of air holes running along the entire length of the fiber. With careful choice of fiber parameters, such as lattice pitch (Λ) and air-hole diameter (d), a large fraction of the optical field propagates through the fiber as an evanescent field, penetrating into samples positioned in the air holes [5]. Fiber Bragg grating (FBG) sensors based on a D-shaped fiber or a side-polished fiber have been widely used to measure the refractive index of different liquids [6]. However, the sensors based on gratings can only be used to measure the RI which is less than that of the fiber cladding, limiting their application range. The structure of RI sensor is like intrinsic Fabry-Perot interferometers (IFPIs) sensor, which is in line fiber Fabry-Perol refractive index tip sensor is based on the combination of an in-line fiber micro-FP cavity, fabricated by using 157 nm laser pilses, and section of SMF [6-7].

Apart from modeling PCF technique transverse scattering can also be used as a refractive index sensing. Transverse scattering has been used in the study of tapered PCF, however it has used in a non-distructive method in probing and profiling the PCF microstucture along the taper [8].

Fig. 1, shows the cross section of typical index-guiding PCF with sixfold rotational symmetry [8]. All silica fiber consist of a solid core with the absence of an air-hole at the lattice side forms a region of raised refractive index, which is surrounded by microstructures cladding, that are typically hexagonal packed, with pitch, Λ and d, the air-hole diameter. This work present transverse scattering correlate with the RI in the liquid filled PCF using FDTD. The types of FDTD techniques used are transverse scattering transmission. OptiFDTD software is used due to its availability software at the moment. The transverse spectrum was analyzed using

PCA. The PCA used as a mathematical tool to model the data obtained by Mathcad software. Many advantages of RI sensor in PCF. For example, high sensitivity, ability for multi-parameters measurement and large measurement range.

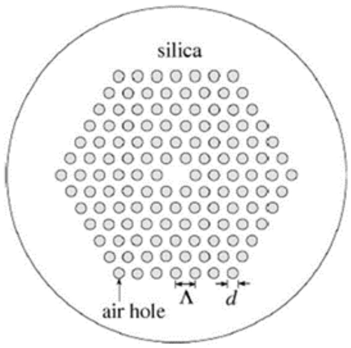


Fig. 1: Photonic crystal fiber (PCF) [7]

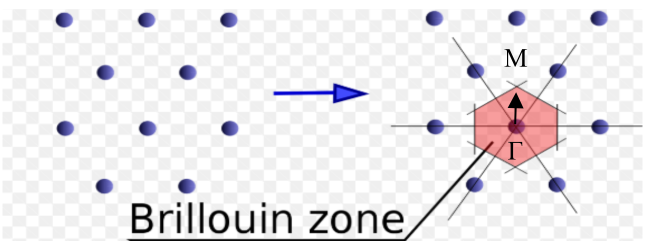


Fig. 2: The corresponding reciprocal lattice inrreducible Brillouin zone

Fig. 2, shows the symmetry axis which is Γ-M direction with TM polarized light in FDTD simulation software. The boundaries of this cell are given by planes related to points on the reciprocal lattice. The importance of the Brillouin zone stems from the Bloch wave description of waves in a periodic medium, in which it is found that the solutions can be completely characterized by their behaviour in a single Brilliouin zone. In mathematics and solid state physics, the first Brillioun zone is a uniquely defined primitive cell is a minimum-volume cell (a unit cell) corresponding to a ssingle lattice point of a structure with discrete translational symetry. The concept is used particularly in describing crystal structure in two and three dimensions, though it makes sense in all dimensions. A lattice can be characterized by the geometry of its primitive cell.

II. METHODOLOGY

In this paper, only the simulation work and the characteristic of the scattering transverse spectrum was correlated with respect to the refractive index of the liquid filled PCF. The simulation was conducted using finite difference Time Domain (FDTD) method [9-10]. The analysis of the transverse transmission spectrum of tapered filled PCF using Principal Component Analysis (PCA) has not been reported to date. As for the analysis of the transmission spectrum there is relationship between the principal component, normalize power and the difference taper size. In result, shows the multiwavelength analysis in 3D score plot. This technique is combined all three component in one plot and it is new in any analysis of PCF by using PCA. The analysis using PCA allows for an accurate characterization of refractive index sensor using a multiwavelength analysis compare to a single wavelength analysis. The correlation of scattering of liquid filled with the refractive index change from 1.33 to 1.43 in photonic crystal holes was also investigated with respect to taper size. Normally in sensing, the refractive index of distilled water which is 1.33 being used as a standard. We want to investigate on how much power being transferred at different taper size and refractive index from 1.33 to 1.43. The reason on the selection range of refractive index is because we do not want the LMA-8 to be a high-power rod-type PCF and used for correlating material inside the crystal. The PCF used in the analysis is LMA-8, with pitch of Λ = 5.6μm, air hole diameter d = 2.74μm, and outer diameter (OD) = 125μm, and the refractive index (RI) = 1.45. In Fig. 3, shows the schematic diagram of PCF in between two SMF. All parameters were set as LMA-8 parameter [12]

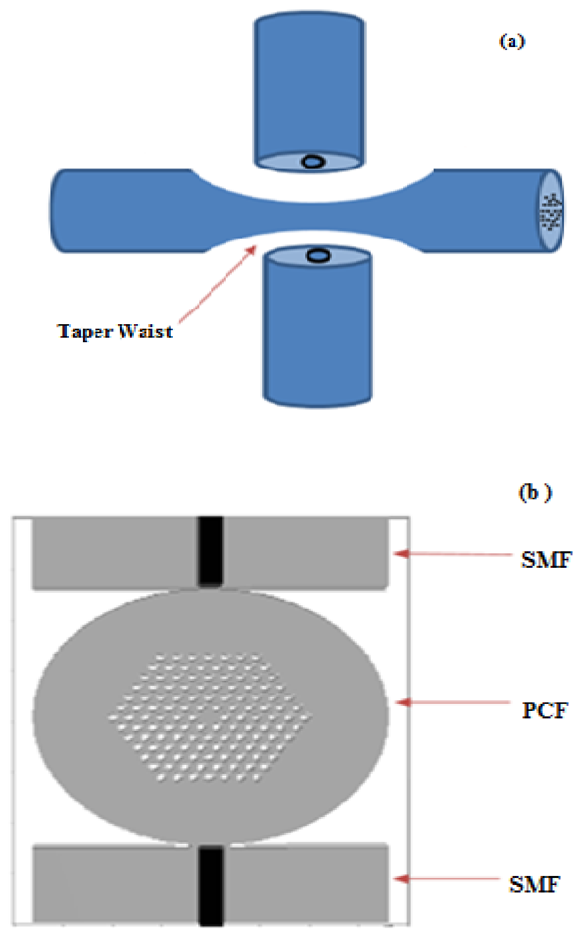


Fig. 3: (a) The tapered PCF is sandwiched between two SMF in 3D structure, (b) The design of tapered PCF is sandwiched between two SMF in 2D structure in simulation software

The first part of this work is to design and model the transverse scattering across the taper structure using OptiFDTD software. In addition, the meshing of the model was ensured to follow Yee's criteria [10], the meshing size is given by equation (1).

$$\Delta = \frac{\lambda n}{10}. \quad (1)$$

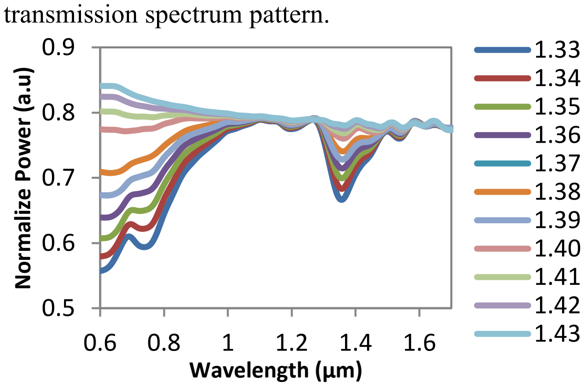
where λ is taken as 0.6 μm which is the lowest wavelength within the simulation range of 0.6 μm to 1.7 μm., and n is the refractive index. The time step used is 15000 steps. Initially, the simulation was investigated between 10000 to 16000 time step and it was found that time step of 15000 is sufficient to provide a consistent result. The simulation presented in this paper refer to the transverse spectrum along Γ- M. The simulation results was then analysed using PCA. PCA is a multivariate technique that analysed a set of data in which observations are defined by several inter-correlated quantitative dependent variables [13]. Its goal is to represent the spetrum in terms of new orthogonal variables called principal components. The data can be expressed as in equation (2).

$$X = Ta\, P'a + Ea = t_1\, p_1' + E_a \quad (2)$$

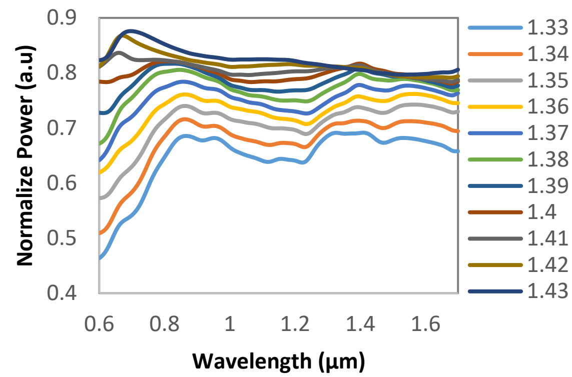
where T_i is score, P_i is loading, and E_i is residuals. The score and loading have obtained from the eigen value and eigen vector analysis of the data. In this paper, more than one principal component modeling of data is performed. The principal component analysis was conducted using MathCad Prime software [15]. Therefore, all spectrum analysed using PCA will give a set of scores the first and second principal componants for the range of refractive index from 1.33 to 1.43.

IV. RESULTS AND DISCUSSION

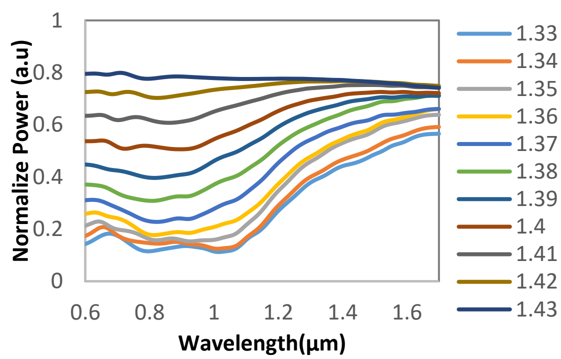
The raw simulated scattering spectrum obtained between 0.6 μm to 1.7 μm are shown in Figs. 4 (a), (b) and (c) for tapered and untapered respectively. It can be seen in the figures that the transmitted power increases as the index difference between the liquid filled holes and PCF decreases. In fig 4 (a) the spectrum of each refractive index are more closer start at wavelength 1.0 to 1.7 μm compare to fig 4 (b) and (c). These shows that, the taper size is affected the transmission spectrum pattern.



(a)



(b)



(c)

Fig. 4: (a) The transmission spectrum vs refractive index change in PCF with respect to 0.1 taper ratio, (b) The transmission spectrum vs refractive index change in PCF with respect to 0.5 taper rati0, (c) The transmission spectrum vs refractive index change in PCF with respect to untaper

In Figs. 5 (a), (b), and (c) are the smoothed scattering pattern of Figs. 4 (a), (b), and (c). The smoothing was done using Kernel gausian smoothing available in Mathcad Prime [14]. Each of the spectrum in figs 5 (a), (b), and (c) represent the transverse transmission spectrum with the liquid filled PCF for RI of 1.33 to 1.43 at 10% tapered, 50% tapered and untapered PCF respectively. Figs 5 (a), (b) and (c) shows the differences of normalize power for 1.33 to 1.43 are about 0.03, 0.16, and 0.70 a.u respectively. Hence, at untapered PCF gives the large value which is 0.70 a.u compare to 10% and 50% taper. Furthermore, untapered is most sensitive.

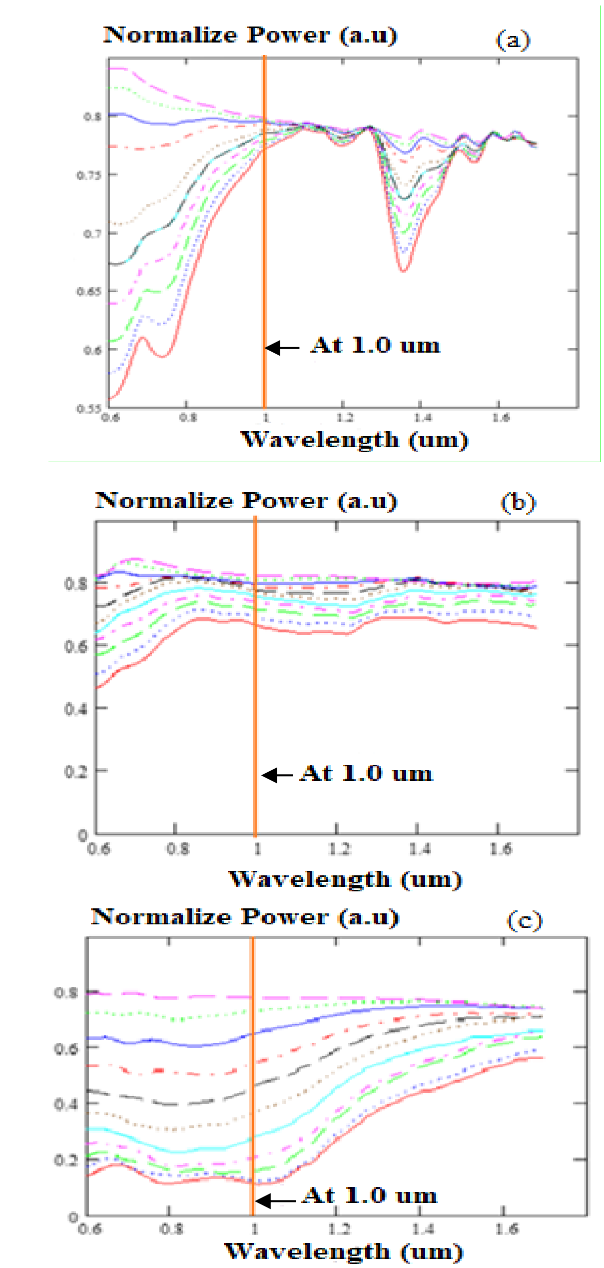


Fig. 5: (a): Scattering pattern of 10% tapered PCF, (b) scattering pattern of 50% tapered PCF, and (c) scattering pattern of untapped PCF

In Fig. 6, the results from Figs. 5 (a), (b), and (c) were analyzed at a wavelength of 1.0 µm. This is because at that wavelength is the optimum spectrum in this simulation.The normalized power is plotted againt RI of the liquid filled holes in PCF. The, sensitivity of the sensor is given by the gradient of the curve in (3) and also linear equation in (4).

$$S=\frac{\Delta P}{\Delta n} \quad (3)$$

$$y=mx+c \quad (4)$$

Where m is represent the gradient of the curve. The sensitivity of each of the curve was calculated to be 0.58, 1.66, and 7.45 a.u/RIU for the tapered size of 10%, 50%, and 100% of PCF size. Therefore, we can concluded that the untapered PCF RI sensor is more sensitive compare to tapered PCF RI sensor. And but this transverse scattering technique is suitable for any range of refractive index as refractive index sensor.

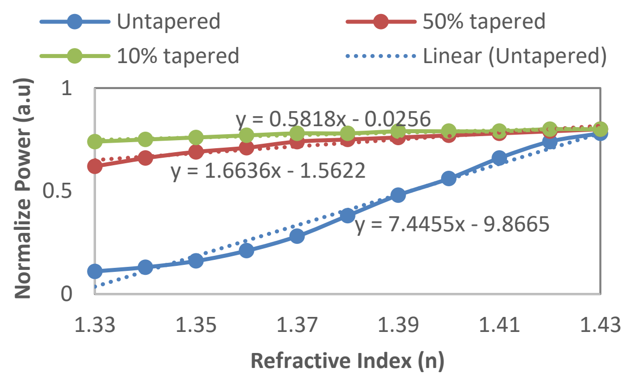


Fig. 6: Normalize power at (1.0µm) of 10%, 50% tapered, and untapered PCF

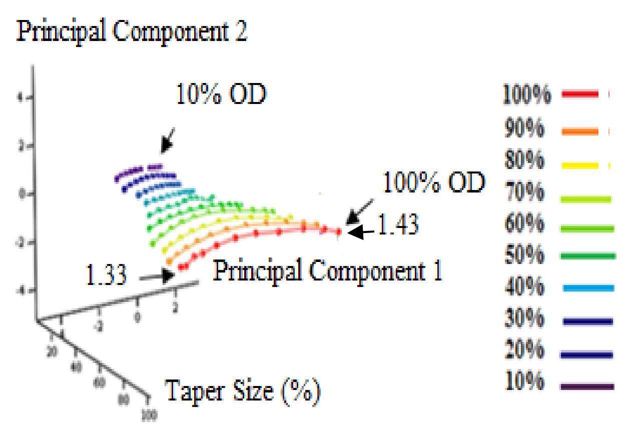


Fig. 7: 3-D score plot of a PCA model of transverse scattering pattern for taper size 10% to 100%

Fig. 7 is the multiwavelength analysis of the transverse scattering of liquid filled PCF. The 3D score plot shows three main axes which are Principal component 1 (a.u.), Principal component 2 (a.u.), and taper percentage size represented by x, y, and z-axes respectively The red line represent the untapered PCF, and each point on the line is the value of the score from the PCA of the spectrum for RI from 1.33 to 1.43. Similarly for the other lines, it represent the scores taper size 90% to 10% of original size. It can be observed that the spread of sets points for untapered PCF is larger compared to tapered PCF. Sensitivity is quantified by the spread of points on each line. The standard deviation and plane values were chosen to constrain the 'spread' across each axis - the most variation along the x-axis and least along the z-axis [16]. For example, for the untaper PCF the different spread of point in each line is larger compared others taper size and this gives more sensitivity. The obtained sensitivity as in table I. the sensitivity of 80% taper size is more sensitive compare to 90% taper size. This was occurred because in terms of holes in PCF and it is not linear. Therefore, untapered is more sensitive compare to others tapered ratio.

TABLE I
THE SENSITIVITY OF REFRACTIVE INDEX SENSOR IN TAPERED PCF.

Taper size (%)	Sensitivity (a.u./RIU)
10	2.81
20	0.31
30	1.08
40	2.02
50	2.11
60	4.74
70	3.96
80	4.72
90	4.20
100	4.76

V. CONCLUSSION

In summary, as for the analysis of the transmission spectrum, the PCF works equally well in tapered and untapered conditions for the correlation of the transverse scattering against the RI change in crystal holes. Hence, there is a relationship between the transmission spectra and the RI in the liquid filled PCF for the taper ratio of analysis over the wavelength range of 0.6 µm to 1.7 µm. Hence, this technique can be used as a RI sensor. We have shows that the sensitivity of the RI sensor base of transverse transmission spectrum is the most sensitive in the untapered PCF.In addition, the sensitivity of RI is more sensitive at untapered PCF. Therefore, the appropriate size for sensing application is the original size of PCF.

VI. REFERENCES

[1] C. Li, S. J. Qiu, Y. Chen, F. Xu, and Y. Q. Lu, "Ultra-sensitive refractive index sensor with slightly tapered photonic crystal fiber," *IEEE Photonics Technol. Lett.*, vol. 24, no. 19, pp. 1771–1774, 2012.

[2] F. Esposito, R. Ranjan, S. Compapiano, and A. Iadicicco, "Arc-Induced Long Period Gratings from Standard to Polarization-Maintaining and Photonic Crystal Fibers," Sensors, vol. 18, 918, 2018.

[3] R. Jha, J. Villatoro, G. Badenes, and V. Pruneri, "Refractometry based on a photonic crystal fiber interferometer," *Opt. Lett*. vol. 34, no. 5, pp. 617–619, 2009.

[4] R. Jha, J. Villatoro, and G. Badenes, "Ultrastable in reflection photonic crystal fiber modal interferometer for accurate refractive index sensing," *Applied Physics Letters*. pp. 23–25, 2008.

[5] J. B. Jesen. L. H. Pedersen, P. E. Hoiby, L. B. Niesen, T. P. Hansen, J. R. Folkenberg, J. Riishede, D. Noordegraaf, K. Nielsen, A. Carlsen, A. Bjarklev, " Photonic crystal fiber based evanescent-wave sensor for detection of biomolecules in aqueous solutions," *Opt. Lett*. Vol. 29. No. 17. September. 2004.

[6] Y. J. Rao, M. Deng, D. Duan, T. Zhu, "In-line fiber Fabry-Perot refractive index tip sensor based on endlessly pgotonic crystal fiber," *Sensor and Actuators A*, 148, pp. 33-38. 2008.

[7] H. C. Nguyen, B. T. Kuhlmey, E. C. Magi, M. J. Steel, C. L. Smith, and B. J. Eggleton, "Tapered photonic crystal fibres: properties, characterisation, and applications," *Appl. Phys. B.* vol 81, pp. 377-387, July 2005.

[8] K. Saitoh, and M. Koshiba, "Numerical Modeling of Photonic Crystal Fibers," *IEEE, Journal of Lightwave Tech,* vol. 23, no. 11, pp. 3580-3590, November 2005.

[9] A. J. Ward and J. B. Pendry, "Calculating photonic Green's functions using a nonorthogonal finite-difference time-domain method," *Phys. Rev. B* 58, 7252-7259, 1998.

[10] L.Zhao, "A Study of Dispersion and Anisotropy Effects for FDTD in Non-Orthogonal Coordinate," *Proceedings of IEEE Antennas and Propagation Society International Symposium and URSI National Radio Science Meeting.* IEEE, pp. 2113-2114, 1994.

[11] H. R. Dehghanpour, H. Alisafaee, S. M. Molavi Arabshahi, "Design of integrated optical circulator based on photonic crystal," *Elsevier, Optik* 125, pp. 3587-3589, January, 2014.

[12] H. Tu, J. Laesgaard, R. Zhang, S. Tong. Y. Liu, S. A. Boppart, " Bright broadband coherent fiber sources emitting strongly blue-shifted resonant dispersive wave pulses," *Opt. Express,* vol. 21, no. 20, 7 October 2013.

[13] H. Abdi, and L. J. Williams, " Principal Component Analysis," John Wiley & Sons, Inc. vol. 2, July/August, 2010.

[14] Principal Component Analysis and Near Infrared Spectroscopy, 2012 [Online] Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.738.7692&rep=rep1&type=pdf [Accessed 17 April, 2010]

[15] Mathcad Prime Software, 2008 [Online] Available: http:www.ptc.com/engineering-math-software/mathcad, [Accessed 23 May 2017]

[16] PCA for 3D, 2017 [Online] Available: https://www.algosome.com/articles/pca-three-dimensions-point-cloud.html, [Accessed 25 May 2017]

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