APLANATIC POINT ANALYSIS OF SOLID IMMERSION LENS IN PHOTONICS

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ABSTRACT

Focusing on the advancement of the technology in the field of photonics since the optical fiber had been developed in the era of 1970s, we are continuously looking on the improvement in resolving power, collection efficiency and magnification to counter the conventional devices. By knowing the motive and the concepts behind BORN and WOLF theory and ray optics concept, various lens combination and designs give rises to Solid Immersion Lens in optical communication. This research work looks at various factors, geometry and arrangements to have better properties, as magnification and spatial resolution are the prime factors in this field of optics. Here in this paper we will show the conditions favoring the converging nature of the resultant lens through four cases; and also we will conclude which cases are better for the converging capacity of the lens and what are the conditions, through the derived formula and snell's law condition applying at each interface of the consecutive material surface. Here case (1) and case (2) are favourable cases and case (3) and case (4) are not favorable but instead the conditions which makes case (1) and case (3)more desirable with respect to other one is explained through the derived condition and formula. Basically this research points to the concept of Solid Immersion Lens (SIL); mostly on weierstrass optics by using ray optics and geometrical optics.

KEYWORDS: *Aplanatic point; Refractive index; h-SIL; Weierstrass SIL; Radius of curvature*

I. INTRODUCTION

A Solid Immersion Len (SIL) has higher magnification and higher numerical aperture than common lenses by filling the object space with a higher refractive-index solid materials. These kinds of lens helps in enhancing the spatial resolution of the materials in the field of optical microscopy. Mostly all the optical microscope have limited diffraction in it because of the wave nature of light passing through it. Current research focuses on techniques to go beyond this limit known as the Rayleigh criterion. By using these Lens we can achieve spatial resolution better than that of the diffraction limit in the air for both imaging techniques i.e. far-field imaging and near- field imaging techniques. Now-a-days solid immersion lens (SIL) is a powerful optical component which plays an important active role in the field of nano photonics and its applications. Since these lens had been invented, they had exploited several technologies in nano science which includes spectroscopy in nanoscale, inspecting semiconductor integrated circuit, photolithography and optical data storage. Inspite of covering all these technologies in optical, these lens have received poor coverage. Experiments in optical are generally carried out with very less spatial resolution it might be in some hundreds nanometers or even less than it. Utmost precision are needed in the investigation in near-field imaging which are drawn with a wide range of techniques in optical microscopy, which requires various combination of equipment or the arrangements of the lens to get the desired results. Solid immersion lens is simply an optical device which will be introduced preliminary in this paper so that further concluded work can be introduced. There is a chain of progressive development in the list of solid immersion lens's evolution actually it started with the technique of liquid immersion as it can find a way to improve the resolving power of sub-surface microscopy, by decreasing the planar geometry effect of air-medium interface, by limiting the factors. With the corrections and various modifications in the interface geometry we can have the good imaging process as discussed above.

The microscopy through solid immersion lens has gained an increasing interest in the field of photonics since it has been invented in 1990[2]. The SIL concept is basically based on the idea discussed above (concept of liquid immersion), but it also includes the concept of light, its critical angle formation spatial resolution and efficiency of beam collection through it.

II. LITERATURE SURVEY

There are various approaches and concepts discussed in this literature about the Solid Immersion Lens (SIL) which helped in making pace with the desired model and concept about SIL and its aplanatic point, which are as follows

E. Ramsay et al. [2] This paper shows the aplanatic solid immersion lens microscopy is required to achieve the highest possible resolution for next generation silicon IC backside inspection and failure analysis; however aplanatic SILs are very susceptible to spherical aberrations introduced by thickness mismatch. Good agreement between theory and experiment is achieved and spot intensity increase by a factor of two to three are demonstrated.

I. Ichimura et al. [3] presented a scenario in which Solid Immersion Lens is attached to conventional object which increases the Numerical Aperture (N.A) of an optical object from (N.Aeff) to (N.Aeff)2. Also this literature showed that, with this N.A, storage density is increased but in sealed system. But in an unsealed environment it has good storage density but not good as the storage density obtained in the sealed one.

B.D. Terris et.al [4] states that Solid Immersion Lens microscopy technology provides the combined advantages of conventional microscopy and near-field technology. This literature involves the SIL-focusing which improves the resolution and the light-collection efficiency of Solid Immersion Lens. It also covers the concepts of fluorescence micro-spectroscopy and sub- surface imaging with spherical-aberration with various consequences regarding aplanatic imaging.

R. D. Younger et al. [5] proposed that the solid immersion microscope has been developed to study a variety of physical systems with high resolution n and we suggest its inclusion in upper level optics courses. Also briefly describe the solid immersion microscope in the context of geometrical optics and a desktop demonstration and use the angular spectrum representation to calculate the focal fields produced by a conventional microscope and a solid immersion microscope. It also suggest a simple model for lens aberration and perform numerically the focal field calculations with and without aberrations to enable users to compare the performance of conventional and solid immersion microscopes. These calculations can help users develop intuition about the sensitivity of microscope performance to real-world manufacturing tolerances and to the limitations and capabilities of microscopy.

B. B. Goldberg et al. [6] described the sub-surface and surface imaging of Solid Immersion Lens microscopy in both experimental and theoretical aspects. He also explained the ability of sharp metal tips to enhance the local optical fields for spectroscopy and nano meter resolution microscopy. He described a new approach of combination of solid immersion microcopy with tip-enhanced focusing.

K. Karrai et al. [7] uses the confocal solid immersion microscopy for diffraction limited focused spot of reflected image. He finds that the spot's image shows aberrations when reflected off objects with optical indexes lower than that of the solid immersion lens (SIL) material. He also demonstrate that such aberrations are only apparent and that the actual size of the spot at the SIL/object interface remains diffraction limited, and the aberrations are due to lateral waves at the SIL surface. He make use of this image aberration in conjunction with the spatial filtering inherent to confocal microscopy in order to dramatically enhance the optical contrast of objects with low optical indexes.

Y. J. Zhang et al. [8] deduce the optical field distribution of the so-called plano-convex solid immersion mirror with a small aperture on the apex (PC-SIM) by using the vector diffraction theory. He showed simulation results as PC-SIM, like a solid immersion lens (SIL), can achieve high resolution, unlike the SIL, the PC-SIM can effectively reduce the spreading of the spot size with increasing distance from the interface. The size and intensity of the spot are related not only to the refractive index of the solid immersion medium but also to the structure parameter of the PC-SIM.

T. Koyama et al. [9] a new backside fault isolation technique based on the concept of the solid immersion lens. This technique improves spatial resolution and also enhance the sensitivity in the infrared-emission microscope (IR-EMS) and the infrared-optical beam induced current (IR-OBIC) technique by directly forming the Si substrate into a hemisphere. She also illustrate that this process of "forming the Si substrate into a solid immersion lens" (FOSSIL) will be a fundamental capability necessary to support the analysis of future minimum geometry devices.

D. A. Fletcher et al. [13] presented the micro fabrication of a solid immersion lens from silicon for scanning near-field optical microscopy, also he explained that the Solid Immersion Lens achieves spatial resolution better than the diffraction limit in air without the losses associated with tapered optical fibers. He formed a SIL by reflowing photoresist in acetone vapor and transferring the shape into single-crystal Si with reactive ion etching. Using the Si SIL, he showed that the micro fabricrated lenses have greater optical transparency and less aberration than conventional lenses. He demonstrated the scanning near-field optical microscopy with the Si SIL and achieve spatial resolution below the diffraction limit in air.

G. M. Morris et al. [10] have determined fundamental limits imposed on the performance of any super resolution strategy; also he analyzed the current super resolution technique and come to the result that these techniques can have their performance considerably augmented, by a brief analysis.

III. CONVERGING POINTS

The concept of SIL comes from the basics prescribed by Born and Wolf. This theory states that light can be focused without aberrations at only two points within a high-index sphere. These focal points are known as the "aplanatic" points of the sphere.

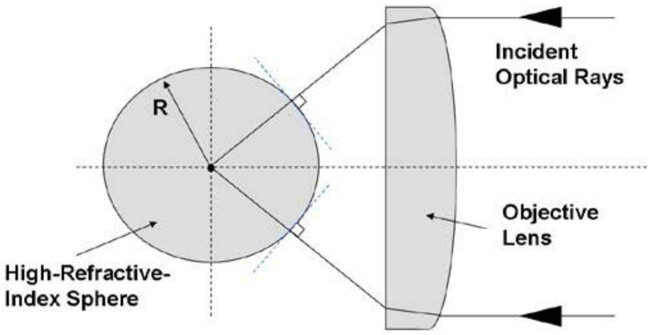

Figure 1: Diagram illustrating the first aplanatic point within a sphere.

The first of those two aplanatic point i.e. the first focal position is located at the center of the sphere, these are those incoming rays which arrives at normal incidence to the surface of the sphere and do not encounter refraction at the air-lens interface. This is the basic condition for the design of a SIL which is h-SIL. Such kind of elements in lens are commonly used to focus the image that lies close to the surface of the sample image component because these elements in lens will be positioning at a focal plane lying immediately below the planar surface of the h-SIL. So this h-SIL is an important component of optical photonics which helps in analyzing the QDs of semiconductor as it provides an opportunity to increase and enhance the collection efficiency of rays as well as to improve the spatial profiling resolution of the sample under investigation. The h-SIL is shown below with all the rays converging to the center of the lens.

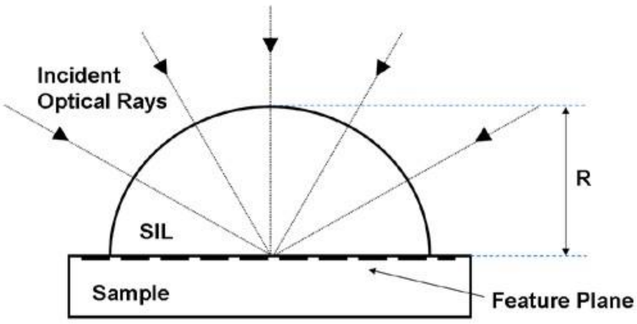

Figure 2: A standard hemispherical solid immersion lens (h-SIL).[5]

Super solid immersion lenses explains the origin of the second aplanatic focal position, which is located at a distance $z_0 = (n_1/n_2)*R$ from the center of the sphere, where *R* is the radius of curvature of the sphere and n_0 and n_1 are the refractive indices of the sphere and the air respectively. Light focused to this point has a virtual focus located outside the sphere at a distance $z_0 = (n_1/n_2)*R$ from its center, which the incident rays are refracted at the air-SIL interface. This condition give rise to the design of a super solid immersion lens (s-SIL) i.e. also known as a Weierstrass Lens or Weierstrass Optics. A major benefit of using an s-SIL stems from its improved magnification properties as compared to the h-SIL. The s-SIL shown below showing second aplanatic point as Z1.

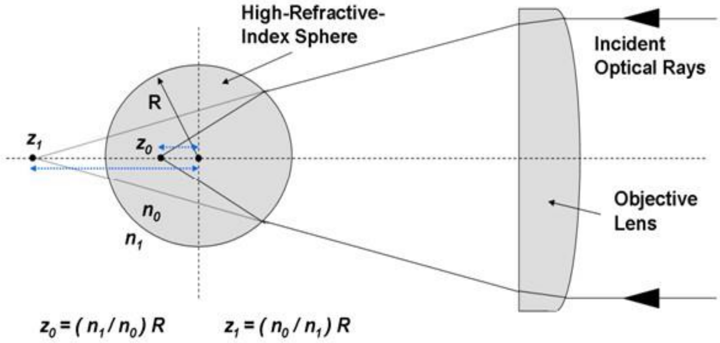

Figure 3: Rays through SIL in different medium.[5]

When one wishes to use a SIL to investigate about the sub-surface features of imaging in a given medium the precaution must be taken to ensure that there must be a good index match between the SIL and the substrate. For surface or sub-surface image enhancement interrogation both h-SIL and s-SIL can be used. Solid immersion lenses can play a vital role in several aspects of photonic characterization and imaging applications. It has been stated earlier in this paper that an h-SIL can produce a magnification to an imaging system at the interface. But in relative terms an s-SIL adds significantly more magnification than h-SIL. The "optical lever" effect helps in understanding the increase of this magnification. When a focused laser beam is offset laterally from the optic axis by some distance on the top surface of a SIL, the resulting focal position moves by a smaller related distance. Not only it plays an extremely important role in the imaging system in whole, but because it was suggested and confirmed that there is an optical lever effect in the axial direction as well. All here we can do is that we can decrease the distance between two focused points i.e. the two aplanatic points in the system. Actually in this paper we are trying to converge the second aplanatic point, nearer to center, on the optical level.

IV. IMPLEMENTS AND FINDINGS

In this research the aplanatic point research is done in weierstrass optics through various medium having different refractive index as shown in figure 4

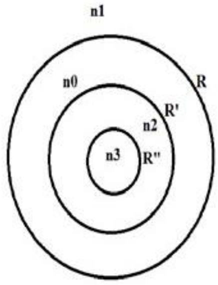

Figure 4: various medium with refractive index and radius of curvature

Here we have four mediums

- Medium1 having refractive index n1 and when light beams passes from medium1 to medium2 it has radius of curvature R.
- Medium2 having refractive index n0 and when light beam passes from medium2 to medium3 it has radius of curvature R'.
- Medium3 having refractive index n2 and when light beam passes from medium3 to medium4 it has radius of curvature R".
- Medium4 having refractive index n3.

Now we have gone through various materials having different refractive index through following process i.e. applying Snell's law when passing from one medium to another as

- $Z0 = \frac{n1}{n2} * R$ (1)
- $Z1 = \frac{n0}{n2} * R'$ (2)
- $Z2 = \frac{n2}{n3} * R"$ (3)

Where,
Z0 is the first aplanatic point achieved while going from medium1 to medium2; similarly
Z1 is the second aplanatic point achieved while going from medium2 to medium3; and
Z2 is the third aplanatic point achieved while going from medium3 to medium4; and so on.

Note: Here n1<n0<n2<n3. That means n (1) has the lowest refractive index followed by n (0), n (2) and n (3).

Now here we will take different cases for the analysis.

V. ANALYSIS AND MATHEMATICS BEHIND

On analyzing various cases by taking different-different refractive index we concluded that the rate of change aplanatic point (Z) is directly in proportion with difference in the refractive index of outermost materials and the change in the radius of curvature while moving from materials having different refractive index. Also the rate of change of aplanatic point is inversely proportional to the difference of the refractive index of inner materials in the structure (proposed structure); and hence can be expressed as

$$dZ = \frac{n(i)-n(i-1)}{n(i+1)-n(i)} * dR \qquad (4)$$

Where,
i = natural numbers starting from 1
Z = position of aplanatic point from
center R = radius of curvature

Basically in this research we conclude that as the light beam passes through various higher refractive medium the aplanatic points comes closer to the center of solid immersion lens. Basically it deals with

$$Z= \frac{low\ refractive\ index}{high\ refractive\ index} * R$$

(5)

So to have minimum Z it should deal with

- Minimum, low refractive index,
- Maximum, high refractive index, and
- Low radius of curvature

Here it should also be concluded that change in the refractive index of the medium1 and medium2 should be less than the sum of change in the refractive index of medium2 and medium3, and change in radius of curvature for the desired results. This conclusion can be followed further for taking the aplanatic more closer to center of the lens for better resolution. Here all we can conclude is that if the sum, of change in radius of curvature from outer material to the inner material having higher refractive index, and the difference of the inner refractive index, should be greater than the difference of the outer refractive index; so that the second aplanatic could come closer. If the sum is lesser, than we can not get the desired results and both the aplanatic will go apart from each other. So ,

n(i+1)-n(i)} + change in R.O.C > n(i)-n(i-1) (6)

where,

i = natural numbers starting from 1

Here we can see that for case1 and case2, it is satisfying the above condition so these cases are favorable; but in case3 and case4 it does not follows the above condition so it is not favorable and also in these cases the two aplanatic points going far from each other. All other cases can be seen and further studied by taking the different materials of different refractive index from the refractive index table given in this paper; and by seeing the above condition we can conclude which case is favorable and which is not.

VI. RESULTS AND DISCUSSION

In the previous sections we have discussed about the Solid Immersion Lens implementation using different Refractive Index materials, so in this chapter we will represent the results obtained. The results can be obtained by simulating the obtained equation (Equation 4) in previous section, taking care of the concepts and conditions given in (Equation 5, 6).

Case 1:

This result is obtained when change in the refractive index of the medium1 and medium2 is less than the sum of change in the refractive index of medium2 and medium3.

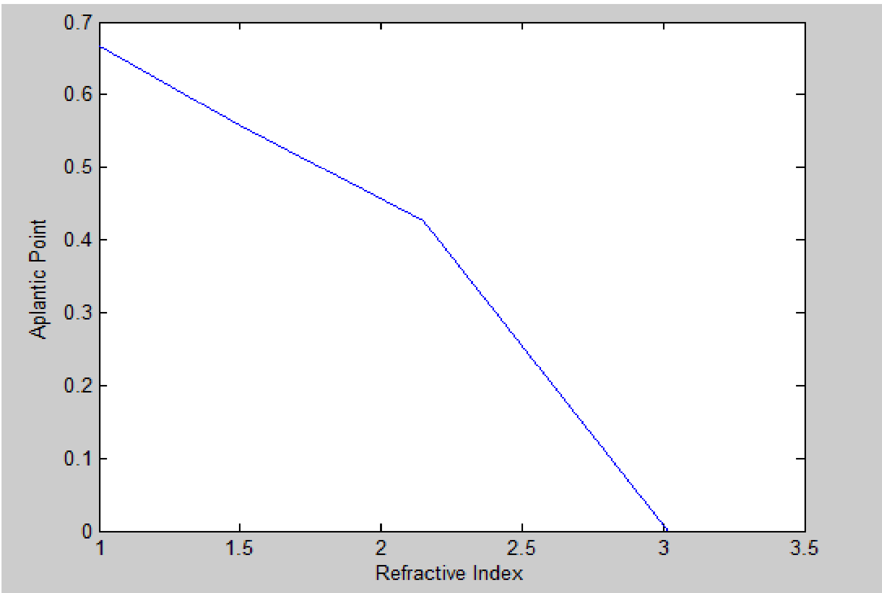

Figure 5: Case (1) implementation

So in above case when passing through medium 1 to medium 2, we got that the difference between both the aplanatic point comes to 0.6667m, and when passing through medium 2 to medium 3, we got that both the aplanatic are 0.5581m apart. Hence in case (1), it can be clearly seen that the change in the refractive index of medium1 and medium2 is less than the sum of change in the refractive index of medium2 and medium3. So the materials taken in medium1, medium2, medium3 and medium4 are respectively n1, n0, n2 and n3.[figure 4]

- n1 = 1
- n0 = 1.5
- n2 = 2.15
- n3 = 3.02

Case 2:

This is same as case (1), as the result is obtained when change in the refractive index of the medium1 and medium2 is less than the sum of change in the refractive index of medium2 and medium3, but the difference between the consecutive refractive index material is reduced.

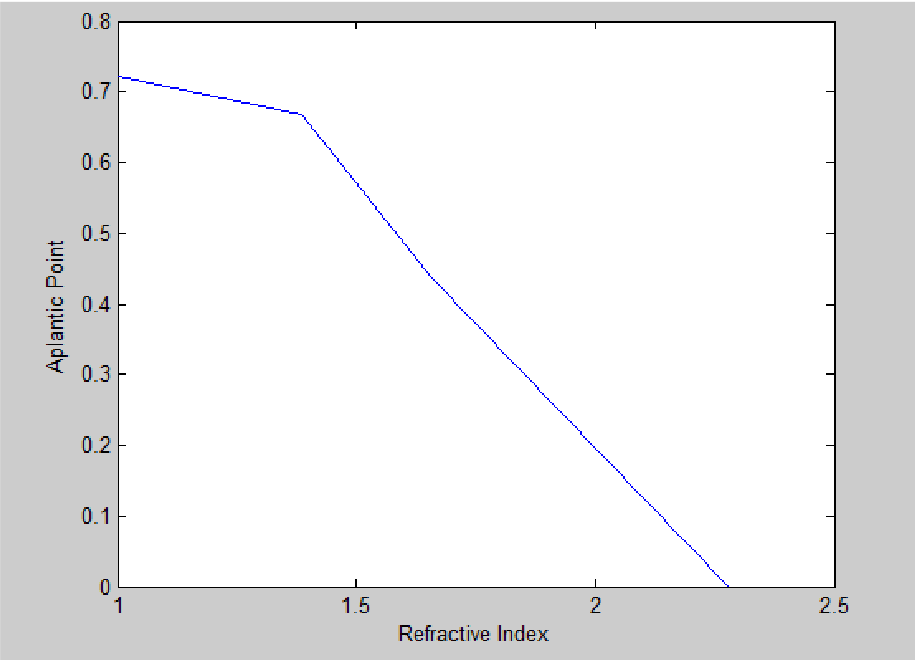

Figure 6: Case (2) implementation

So in above case when passing through medium 1 to medium2, we got that the difference between both the aplanatic point comes to 0.7215m, and when passing through medium2 to medium3, we got that both the aplanatic are 0.6680m apart. Hence in case (2), it can be clearly seen that the change in the refractive index of medium1 and medium2 is less than the sum of change in the refractive index of medium2 and medium3; but the difference between medium1 and human medium2 in case (1) is reduced than the difference between medium1 and medium2 in case (2). Hence for case(2) different material used are respectively

- n1 = 1
- n0 = 1.386
- n2 = 1.66
- n3 = 2.28

We had the comparative study of case (1) and case (2) and found that the case (1) is much better than the simulated result of case (2). Hence conclusion can be made that the difference between the consecutive material of different refractive index should be more, when change in the refractive index of the medium1 and medium2 is less than the sum of change in the refractive index of medium2 and medium3.

Comparison between case (1) and case (2):

Here in graph below we can see that both cases{case1(red) and case2(blue)} are of converging nature and that is why the second point i.e. second aplanatic point is moving towards the center; and one more thing we can notice here is that the second aplanatic point can converge more rapidly towards the center if there is greater difference between the two consecutive refractive indices i.e. we can clearly see that in case1 the difference between two consecutive refractive index is greater than the difference between two consecutive refractive index in case2.

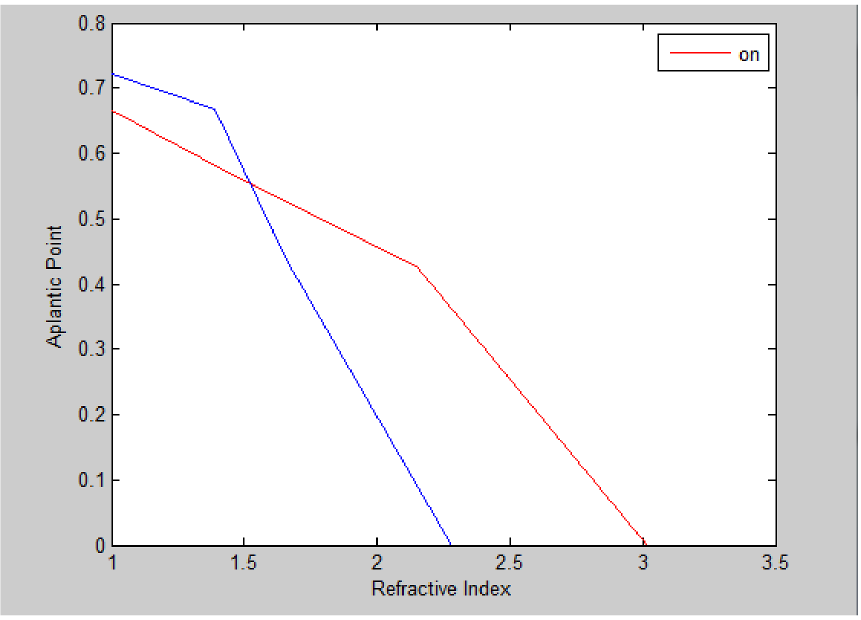

Figure 7: Graph 1(Comparison between case 1 and case 2)

Case 3:

This result is obtained when change in the refractive index of the medium1 and medium2 is greater than the sum of change in the refractive index of medium2 and medium3. So in case (3) we have taken material of refractive index as

- n1 = 1
- n0 = 1.386
- n2 = 1.4729
- n3 = 1.66

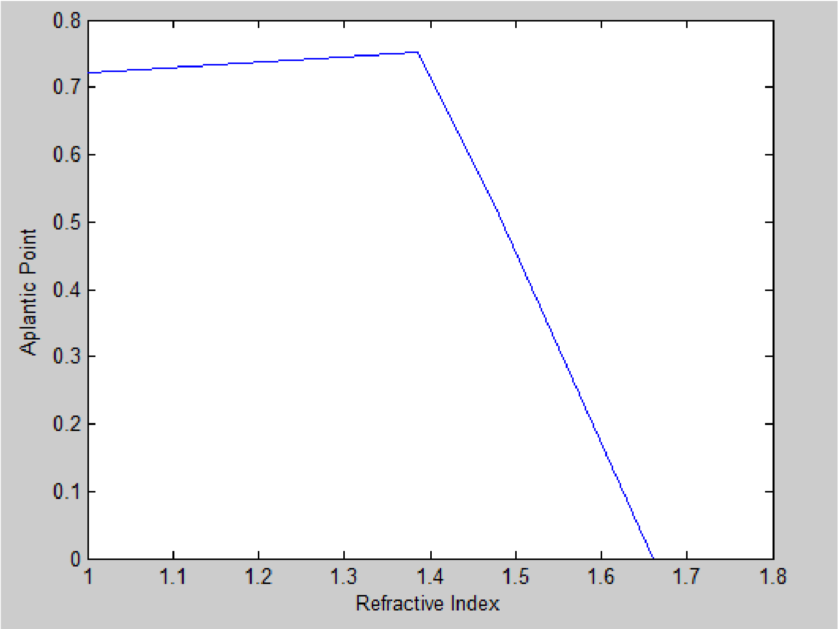

Figure 8: Case (3) implementation

So in above case when passing through medium1 to medium2, we got that the difference between both the aplanatic point comes to 0.7215m, and when passing through medium 2 to medium 3, we got that both the aplanatic are 0.7528m apart. Hence it can be noticed that the refractive index of medium1 and medium2 is greater than the sum of change in the refractive index of medium2 and medium3.

Case 4:

This case is same as case (3), as there is change in the refractive index of the medium1 and medium2 is greater than the sum of change in the refractive index of medium2 and medium3; but the difference between the consecutive refractive index material inside the SIL is reduced. Here in this case we use the different refractive index as

- n1 = 1
- n0 = 1.35
- n2 = 1.36
- n3 = 1.39

So in above case when passing through medium 1 to medium 2, we got that the difference between both the aplanatic point comes to 0.7407m, and when passing through medium 2 to medium 3,we got that both the aplanatic are 0.7941m apart. Hence it can be noticed that there is change in the refractive index of medium1 and medium2 is greater than the sum of change in the refractive index of medium2 and medium3; but the difference between the consecutive refractive material inside the SIL is reduced.

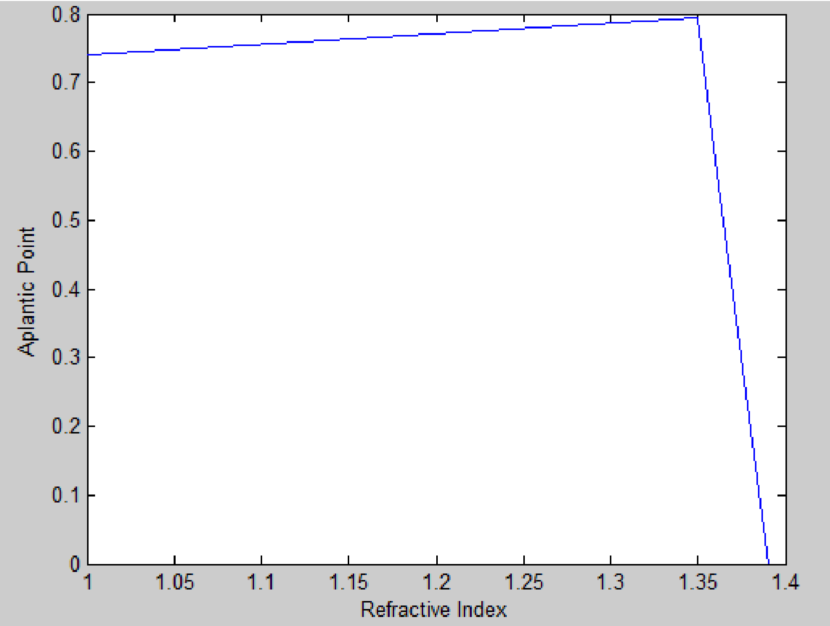

Figure 9: Case (4) implementation

Comparison between case (3) and case (4):

Here we can see in case3 and case4 that the second aplanatic point instead of coming towards center it is moving away from the center. So these cases {case3 (red) and case4 (blue)} conclude that if the inner refractive index of the material is increased with the smaller difference than the aplanatic point will move away from the center accordingly.
All the above cases are analyzed further that what the conditions are affecting the convergence of aplanatic point to the center to get the better beam efficiency and better spatial resolution.

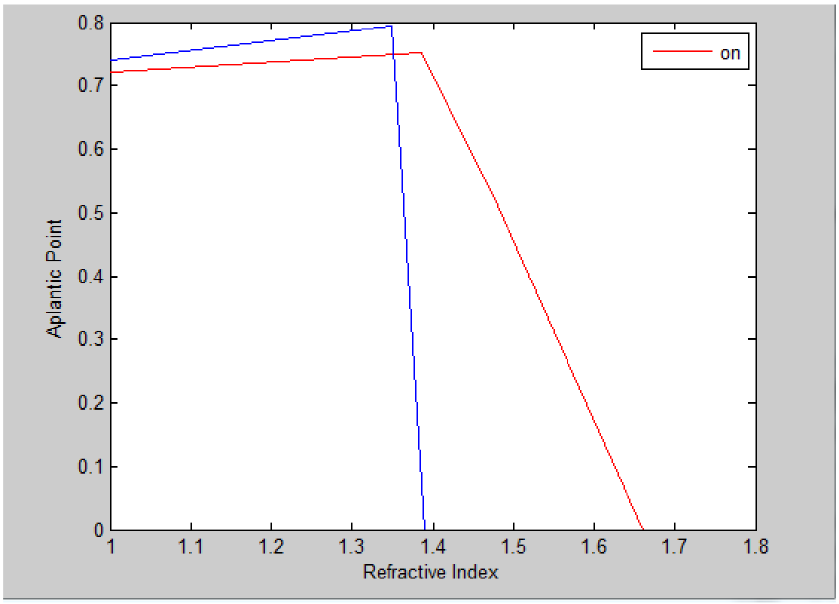

Figure 10: Graph 2 (Comparison between case 3 and case 4)

Note: The various refractive index value above are taken from the refractive index table given at the end of this paper.

VII. Conclusion

Refractive Index Table

Table i.

01	Titanium Dioxide	2.614
02	Diamond	2.419
03	Strontium Titanate	2.41
04	Amber	1.55
05	Fused Silica	1.458
06	Sodium Chloride	1.544
07	Benzene	1.501
08	Carbon Disulfide	1.628
09	Carbon Tetrachloride	1.461
10	Ethyl Alcohol	1.361
11	Silicon Oil	1.336
12	Water	1.333
13	Liquid Helium	1.025
14	Cornea	1.373
15	Lens(Human)	1.386
16	Acetone	1.36
17	Ethanol	1.36

18	Glycerol	1.4729
19	Bromine	1.661
20	Teflon AF	1.315
21	Teflon	1.35
22	Sylgard 184	1.4118
23	Acrylic Glass	1.490
24	Polycarbonate	1.584
25	PMMA	1.4893
26	PETg	1.57
27	PET	1.5750
28	Kerosene	1.39
29	Pure Crown Glass	1.5
30	Pure Flint Glass	1.6
31	Impure Crown Glass	1.485
32	Impure Flint Glass	1.523
33	Pyrex	1.47
34	Cryolite	1.338
35	Rock Salt	1.516
36	Sapphire	1.762
37	Cubic Zirconia	2.15
38	Potassium Niobate	2.28
39	Silicon Carbide	2.65
40	Cinnabar	3.02
41	Gallium Phosphide	3.5
42	Gallium Arsenide	3.927
43	Zinc Oxide	2.4
44	Germanium	4.05
45	Silicon	3.48

In this paper, these are the materials whose refractive can be used to verify our results.

VIII. FUTURE WORK

In this research, simple Solid Immersion Lens (SIL) have been converted into a multiple layer Solid Immersion Lens i.e. SIL have been filled up with various materials having different refractive index [Table 4.5]. Here in this research we have applied the concepts of geometrical optics in the internal structure of Solid Immersion Lens and hence applied Snell's law at the different medium interface. A future scope is there in developing such type of lens practically in the optical lens design laboratory to have a better SIL imaging and better resolution then the conventional one. This research could be taken further and along with the aplanatic point analysis the work can be done on Numerical Aperture (N.A.) simultaneously.

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