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A device for generating collimated polychromatic light and for concentrating scattered light from a fluid

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Abstract. Here we have designed a device that can collect most of the light emitted by a long cylindrical source of polychromatic light and collimate it in a intense narrow beam of light. Different possible aberration are taken care of and losses are considered. We discuss an important application of this design concentrating scattered light coming from a fluid, for example in the case of Raman scattering.

Keywords. Intense collimated polychromatic beam, scattered light from a fluid, Huygens principle in cylindrical symmetry.

1. INTRODUCTION

Light and its strange behaviors have astonished physicists for centuries. From the very early days of Newton, optical experiments have become an essential part of physics. One equipment that is essential for most of the optical experiments is a white light source. And most often it also needs to be a source of parallel beams.

To get a light source like this, is not so easy. There are some conventional methods with a pin hole and collimators but they are not that efficient. One actually eliminates about 95% of the light that is emitted by the main source like a filament bulb or a gas tube, so the 95% of the electrical energy that we put in is also wasted. Importantly, the resulting source is of very low intensity, because of which the observations become very difficult and inefficient.

Here I have designed an equipment that can give us highly intense white light source utilizing most of the energy radiated from the main source as light. We will discuss that this devices light gathering ability can be very useful for certain cases like Raman's scattering experiment where we have to do spectral analysis of light scattered from a liquid. As the scattered intensity varies as $\frac{1}{\lambda^4}$ it becomes very difficult to do the measurements in high wavelength range. Here using this device we can have the maximum intensity possible.

2. WAVEFRONTS DUE TO AN INFINITELY LONG PERFECTLY CYLINDRICAL LIGHT SOURCE

If we consider an infinitely long cylindrical light source of coherent light then, according to Huygen's principle [1], each point on its surface would act as a secondary source. The secondary wavelets generated from those points would eventually superpose and create another wave front of same phase at λ distance apart. Now as shown in Fig.1 all the wavefronts will be coaxial cylinders and the rays will be perpendicular to the wavefronts hence with the axis. This is kind of obvious because as there is cylindrical symmetry the rays will not know any other direction except radial direction. First we will discuss this situation and discuss creation of collimated light from such a source. This situation will be useful for concentrating light scattered from fluids using a laser light source (as for Raman scattering experiments) as we will discuss in section 4. Later we will discuss that even for incoherent light, the geometry of the set up should lead to significantly intense collimated light beams.

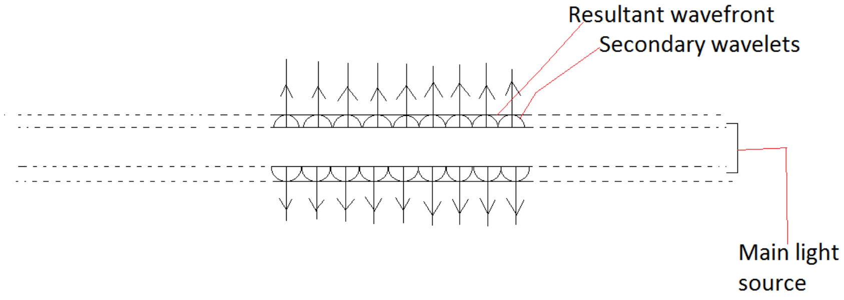

Figure 1. Wavelets and wave fronts for a cylindrical source of coherent light

3. DESIGN FOR COLLIMATED LIGHT SOURCE

The design for collimated intense light source has two parts i) Concentration of incoming parallel beams as efficiently as possible. ii) Production of parallel beams from a perfectly cylindrical gas tube. We will discuss each of them in details below.

For efficient concentration of incoming parallel beams, the usual method of doing this uses two lenses of different focal lengths. One lens has be of larger aperture than other. They must be aligned in such a way that the rays get focused in the focus point of smaller lens by the larger lens. This setup suffers from chromatic aberration as the focal length for different colors would be different (unless one is using achromatic lens combinations). Though for usual laboratory experiments the aberration can be neglected but it is better to use parabolic mirrors. In our setup we will use the parabolic mirror so the issue of spherical aberration is also eliminated [2]. The arrangement of mirrors is shown in the Fig.2. The calculation for output intensity with respect to the intensity of incident ray is shown below.

According to the polar equation of parabola

$$r = \frac{2f}{1 - cos\phi} \tag{1}$$

Now here $OA = r_2$ and $OB = r_1$ as shown in Fig.2 (taking the focus of each parabola to be the same point.)

$$Now \ \ r_2 = \frac{2f_2}{1 - cos(\phi)} \ \ for \ \ secondary \ \ mirror$$

$$r_1 = \frac{2f_1}{1 - cos(\phi)} \ \ for \ \ primary \ \ mirror$$

Now clearly

$$\frac{r_2}{r_1} = \frac{f_2}{f_1} \tag{2}$$

And also

$$\frac{r_2}{r_1} \simeq \frac{a_2}{a_1} \tag{3}$$

Now from equation(2) and equation(3)

$$\frac{f_2}{f_1} = \frac{a_2}{a_1}$$

And we also know that $I \propto \frac{1}{a^2}$, so we can write:-

$$I_2 = I_1(\frac{f_1}{f_2})^2$$

Here:- f_i= focal length of ith mirror
And a_i= aperture of ith mirror
I_1= intensity of incoming beam
I_2=intensity of outgoing beam

Now we will discuss how to produce parallel beams from a long cylindrical light source.

Main part of the device is conical mirror of angle 45° and a long cylindrical light source. The arrangement is shown in the Fig.3. Here we have to keep one thing in mind that the diameter of the cylindrical gas tube should small compared to its length (say, less than 5% of its length). This has to be done because the cylindrical source is of finite length and to minimize its edge effect this source have to be very thin compared to its length. The full setup has three parts as shown in Fig.3, the parallel beam emitter, absorber of imperfections and concentrator. As we discussed earlier, cylindrical source will lead to emission of rays which are normal to the cylindrical axis (for coherent light source). 45° angle conical mirror will convert these rays into parallel light beam. The absorber of imperfections part is actually a cylindrical channel between other two remaining

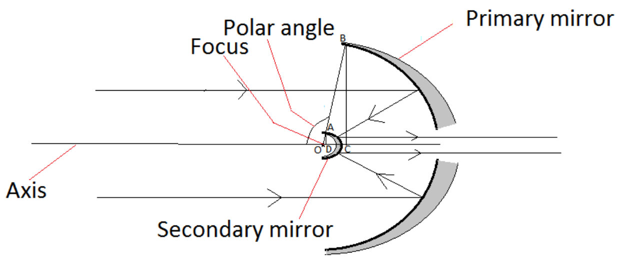

Figure 2. Arrangement of the mirrors for the concentrator

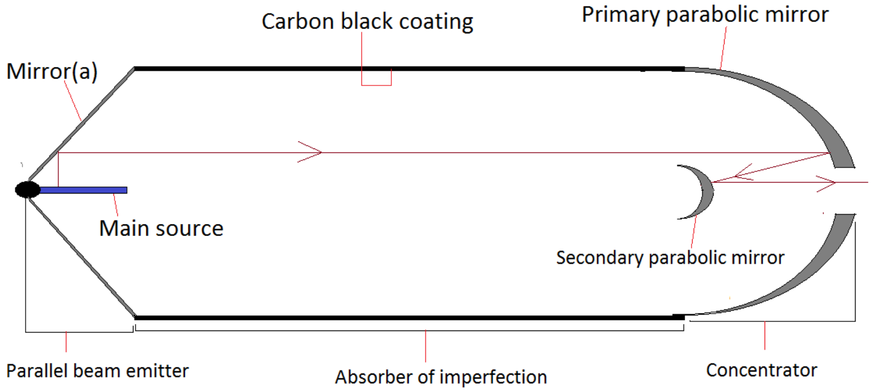

Figure 3. The device

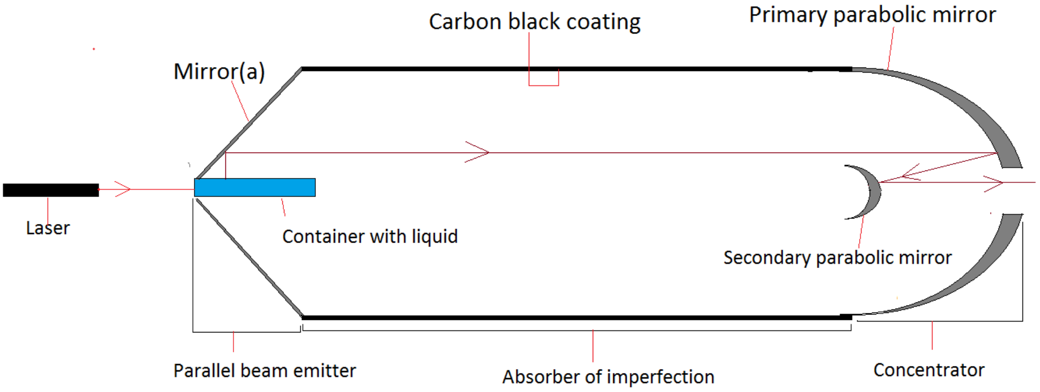

Figure 4. Modified setup for concentrating scattered light from a fluid, e.f. for Raman scattering

parts with carbon black coating on the wall. The middle part is there to absorb all the rays that are not parallel to the axis of the whole device thus eliminating the imperfections. This will take care of the edge effects when the cylindrical light source is coherent. For incoherent cylindrical light source there will be a good fraction of light even from the cylindrical part which will not form parallel beam and this middle portion will absorb all that. Basically, for incoherent light source, the use of cylindrical geometry of light source will help in getting strong intensity for parallel beam. This parallel beam will then be focused by the third part which is the parabolic concentrator finally leading to intense thin collimated light source. As we mentioned, use of parabolic mirrors eliminates chromatic aberration hence white light source (as from a tubelight) can also be used to get collimated white light beam.

4. MODIFIED VERSION OF THE DEVICE FOR CONCENTRATING SCATTERED LIGHT FROM A FLUID

We now discuss an important application of this device for experiments where one has to study the spectrum of scattered light from a fluid, like the experiment of Raman Effect. For this purpose, we replace the main cylindrical light source of Fig.3 (e.g. gas tube) with a cylindrical cylindrical container with the sample fluid. (The setup will work for the liquid sample as well as gas sample.) One plane of the container will be transparent and the liquid will be illuminated by a high intensity laser beam through that side. Now the liquid will act as a new cylindrical source, with the scattered light emanating from the tube propagating in the perpendicular direction to the cylindrical axis (as discussed in Sec.1). Rest of the mechanism is same as in Fig.2. Here all the scattered light will be gathered and concentrated to a thin intense beam. The original laser light propagating along the cylindrical axis should be absorbed either at the end of the tube containing the fluid, or at the back of the parabolic mirrors (with appropriate black coatings). The final collimated beam emerging from the parabolic concentrators will almost entirely consist of the light scattered from the liquid, significantly increasing the intensity of the scattered light for experimental analysis. The schematic diagram of the arrangement is shown in Fig.4.

One experiment that can get benefited from this device is the Raman's scattering experiment. We know that the intensity of Raman lines is very low especially the anti stokes line as the probability of anti Stoke transition is very low [2]. So if we use this device we can measure the wavelength of those lines more efficiently. Many other UV and NIR based spectroscopies can also get benefited from this device as they also face similar kind of problems due to low transition probability of certain lines.

5. DISCUSSION AND CONCLUSIONS

There are several points one needs to be careful about for efficient functioning of this device. The main light source has to be perfectly cylindrical for the main argument of Sec.1 to hold. Also, the diameter of the circular cross-section of the cylindrical light source must be small compared to the length of the cylinder. This is because the wave front emitting from the gas tube is assumed to be perfectly cylindrical but in reality there will be slight curvature at the edges of the cylindrical wave front. To minimize this, the gas tube has to be made longer in compare to its diameter. Again, we emphasize that the argument of Sec.1 holds for coherent light source. For Raman scattering experiment (as discussed for the modified device in Sec.3) where original source is a laser, the scattered light will have strong coherent component, hence the device should work efficiently for that. Even for incoherent light source (such as ordinary tubelight for white light source), the geometry of the device (with long cylindrical source and 45° conical mirror) one should expect production of intense collimated beam. One important part of the device is the mid section which has to be coated black to absorb all the imperfect rays. So the mid section of the device has to be sufficiently long enough to make sure that the rays that are reaching the concentrator are almost parallel to the axis of the device. It should be clear that this design will work perfectly for sound waves as well. For reasonable size of the device, one can have cylindrical source of ultrasonic waves (having coherent source will be easy for sound waves). Then, with all the reflectors designed for sound waves, the device should be able to produce thin collimated beam of ultrasonic waves which can have many applications.

6. ACKNOWLEDGMENT

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References

[1] Ajoy Ghatak, ”Optics”, 6th edition, McGraw Hill Education India Private Limited

[2] Wikipedia, https://www.wikipedia.org