A Semi-Imaging Light Pipe for Collecting Weakly Scattered Light

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A semi-imaging light pipe for collecting weakly scattered light

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Abstract

A simple reflective light pipe, formed from a cylindrical tube with an external reflective coating and a small central aperture, can be a highly efficient optical element for collecting light from molecular scattering processes along the path of a laser beam. When the laser beam is co-linear with the axis of the light pipe, scattered light from any location along the interaction region (near the pipe axis) re-images repeatedly to another location along the axis of the pipe. This semi-imaging property of the light pipe permits a large fraction of the total scattered light to re-image along the entire length of the interaction region. If one observes through the small central aperture, scattered light from the single segment of the laser beam in view appears to come from all the locations along the interaction length, as well as from the single segment. In this manner, one can have the advantage of collecting scattered light from a small segment (and thus onto a small detector), while observing an effective interaction length that is many times longer than the segment. Measurements from practical light pipes confirm effective gains of about 10X with light pipes a few centimeters long (Effective gain is defined as the ratio of light collected with the light pipe divided by the light collected from a direct image of the beam using the collection optics).

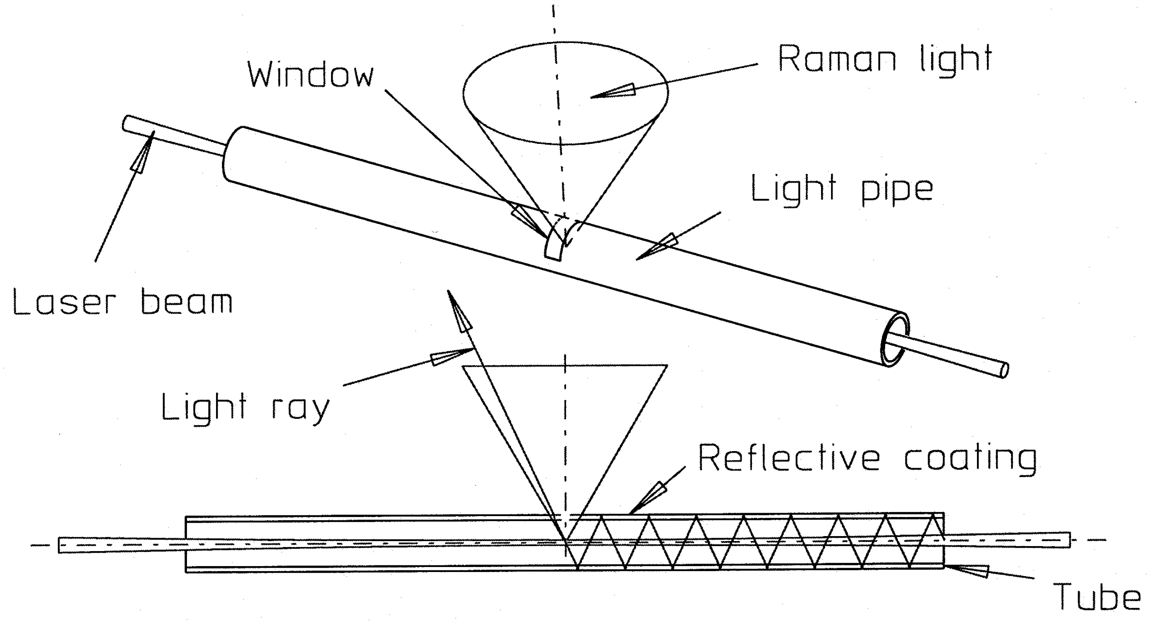
Summary and Description

We designed and tested light pipes in order to enhance optical signals from Raman scattering in atmospheric gases. In the past, observers of weak scattering phenomena, such as Raman scattering, struggled to obtain adequate signals. Balancing the choices of detectors, collection optics and scattering regions, observers make trade-offs. With large detectors, many observers fold the interaction region into a smallish area and collect light with a high numerical aperture.

Instruments with small detectors, such as an element of a diode array or a CCD, will often observe a small interaction length using high NA optics, and add a spherical mirror to re-image forward-scattered light into the NA (for a maximum gain of 2X over direct observation).

Light pipes are used in other applications to provide a longer path length, using end excitation and collection. An example is a gas cell for a Fourier transform infrared spectrometer. Imaging properties of the light pipe are not used in this application.

In our application, a light pipe allows the observation of a very long interaction length, while collecting light at high NA from a small source area. The light pipe design is shown below.



In the simplest embodiment, the light pipe is a hollow cylinder with a reflective interior surface and a small aperture for light to escape.

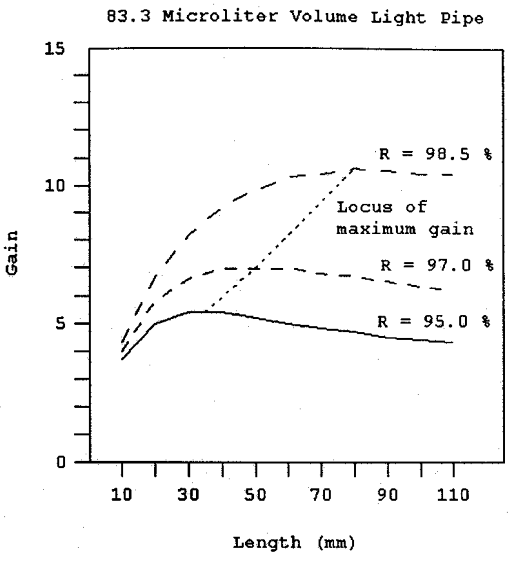
We fabricated light pipes by depositing reflective coatings on the outside surface of precision quartz tubing. Suitable reflective coatings include metals (gold, silver and aluminum) and multi-layer dielectric mirror coatings. The choice of coating should suit the application. Silver is an excellent coating for visible wavelengths; gold is well suited to the NIR and IR. Multi-layer dielectric coatings offer the highest potential internal reflectivity for a given application, but the reflectivity may vary strongly with wavelength, the coating may not have sufficient reflectivity over an adequate range of wavelengths, or the coating may fluoresce.

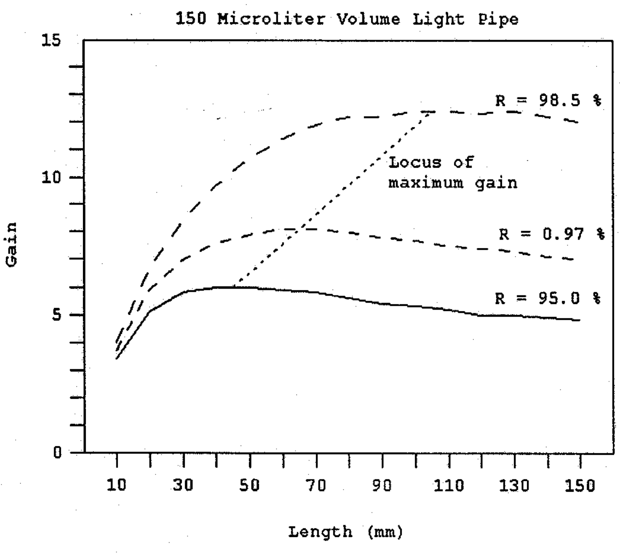
We created a window on the light pipe by removing a portion of the reflective coating at the center of the tube length, while leaving the glass substrate intact (to contain gas samples). The arc of the window, or aperture, should be at least as much as the maximum collection angle of the optics, but not greater than 180 degrees, i.e., half way round the tube.

A numerical model of optical performance

Different choices of tube diameter *d*, tube length *L*, coating type (reflectivity, *$R(\lambda)$)*, and width of the aperture *w* affect the performance of the light pipe. The size and divergence of the laser beam, the size of the detected region, and the collection numerical aperture also affect the performance and the optimum choice of light pipe parameters.

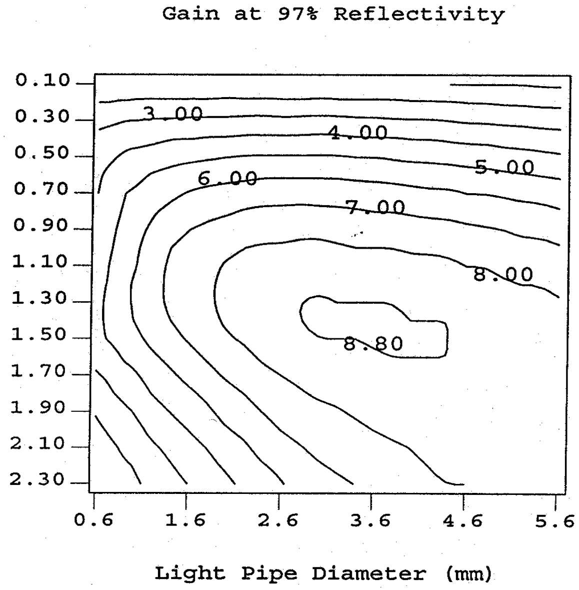
In order to guide our selection and testing of light pipes, we created a numerical model of light pipe performance. We used a Monte-Carlo model of light scattered from a laser beam with a Gaussian intensity profile and ray tracing. We simulated the paths of rays from scattering events, reflected from a coating of known reflectivity, and computed the fraction of light that eventually emits from the light pipe aperture into collection optics. The plots below are for a 1.6 mm detector height, a 675 nm laser beam with a center waist (w_0) of 0.100 mm and a silica tube wall of 0.2 mm. The collection focal ratio is f/1.2. Aperture width is the optimum width.





Narrow apertures (*w<d*) provide a image with a uniform flux distribution, but limit the total flux collected. Wide apertures (w>d) have a non-uniform image, with much of the light concentrated at the edges of the image. Such an image may result in greater flux collection than any smaller image, but a larger detector is required. The optimal aperture width is in the range 0.6*d* < *w* < *1.5d*, a result of wanting a small detector for lower cost and dark current.

The figure below is a contour plot of effective gain for a 60mm long light pipe with 97% effective reflectivity (characteristic of an evaporated silver coating), as a function of tube internal diameter and aperture width (y-axis). The other parameters are the same as for the previous plots.



Measured performance of light pipes

We built light pipes with many different coatings, lengths, and aperture widths and measured their effective gain. The measurements of effective gain follow the trend of the predicted curves for constant reflectivity coatings. However, from these data and measurements on planar witness pieces, we observed that the effective reflectivity of the interior surface of the light pipes was consistently less, by 10 to 30 percent, than would be predicted for a high quality coating on a smooth substrate. These differences may be due to properties of the silica substrate (surface roughness or absorption) or to coating variations that result from coating the cylindrical substrates.

As predicted, we observed that the effective gain of the light pipe is a strong function of the effective reflectivity of the coating. Better coatings resulted in significant improvements in gain; gains of 40 or more have been measured with multi-layer, dielectric coatings, at a single wavelength.

Factors that reduce the effective gain are the alignment of the laser beam in the light pipe, the divergence of the Gaussian laser beam along the tube length and imperfections in fabrication. Misalignment of the laser beam normal to the collection axis results in a wider image of the beam; misalignment along the collection axis spreads the image.

The effect of the diverging Gaussian beam (an unavoidable reality) is to create regions of scattering that increase off-axis with increasing distance from the aperture (We place the waist of the laser beam at the center, from end to end, of the light pipe). When scattered light re-images at the aperture from these regions, it broadens the size of the image (which would broaden a line in a spectrograph, for example). Divergence of the laser beam also places a practical limit on the maximum effective gain, due to intrusion of the light pipe into the laser beam.

Acknowledgements

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References

These references cover both the light pipes described above and their application to Raman gas monitoring in greater detail.

Carlsen et al. - U. S. Patent 5,450,193, *Raman spectroscopy of airway gases.*

Carlsen et al. - U. S. Patent 5,505,678, *System for collecting weakly scattered electromagnetic radiation.*