

For example, assuming an LED with a spectral rms deviation of about 20 nm, and a  $D_w$  200 ps km<sup>-1</sup> nm<sup>-1</sup> (at about 850 nm) we would find the material dispersion as

$$\tau_{\text{material}} = (200 \text{ ps km}^{-1} \text{ nm}^{-1})(20 \text{ nm})(1 \text{ km}) = 4000 \text{ ps km}^{-1} \text{ or } 4 \text{ ns km}^{-1},$$

which is substantially smaller than the internode dispersion and can be neglected.

**2.11 A water jet guiding light** One of the early demonstrations of the way in which light can be guided along a higher refractive index medium by total internal reflection involved illuminating the starting point of a water jet as it comes out from a water tank. The refractive index of water is 1.330. Consider a water jet of diameter 3 mm that is illuminated by green light of wavelength 560 nm. What is the  $V$ -number, numerical aperture, total acceptance angle of the jet? How many modes are there? What is the cut-off wavelength? The diameter of the jet increases (slowly) as the jet flows away from the original spout. However, the light is still guided. Why?



Light guided along a thin water jet. A small hole is made in a plastic soda drink bottle full of water to generate a thin water jet. When the hole is illuminated with a laser beam (from a green laser pointer), the light is guided by total internal reflections along the jet to the tray. Water with air bubbles (produced by shaking the bottle) was used to increase the visibility of light. Air bubbles scatter light and make the guided light visible. First such demonstration has been attributed to Jean-Daniel Colladon, a Swiss scientist, who demonstrated a water jet guiding light in 1841.

### Solution

$V$ -number

$$V = (2a/\lambda)(n_1^2 n_2^2)^{1/2} = (2 \times 1.5 \times 10^{-3} / 560 \times 10^{-9})(1.330^2 1.000^2)^{1/2} = \mathbf{15104}$$

Numerical aperture

$$\text{NA} = (n_1^2 n_2^2)^{1/2} = (1.330^2 1.000^2)^{1/2} = \mathbf{0.8814}$$

Total acceptance angle, assuming that the laser light is launched within the water medium

$$\sin_{\text{max}} = \text{NA}/n_0 = 0.8814/1.33 \text{ or } \theta_{\text{max}} = 41.4^\circ.$$

Total acceptance  $2\theta_a = \mathbf{82.8}$

Modes  $= M = V^2/2 = (15104)^2/2 = \mathbf{1.14 \times 10^8 \text{ modes}}$  (~100 thousand modes)

The cutoff wavelength corresponds to  $V = 2.405$ , that is  $V = (2a/\lambda)\text{NA} = 2.405$

$$\lambda_c = [2a\text{NA}]/2.405 = [(2)(4 \text{ m})(0.8814)]/2.405 = \mathbf{3.5 \text{ mm}}$$

The large difference in refractive indices between the water and the air ensures that total internal reflection occurs even as the width of the jet increases, which changes the angle of incidence.

**2.12 Single mode fiber** Consider a fiber with a 86.5%SiO<sub>2</sub>-13.5%GeO<sub>2</sub> core of diameter of 8 μm and refractive index of 1.468 and a cladding refractive index of 1.464 both refractive indices at 1300 nm

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