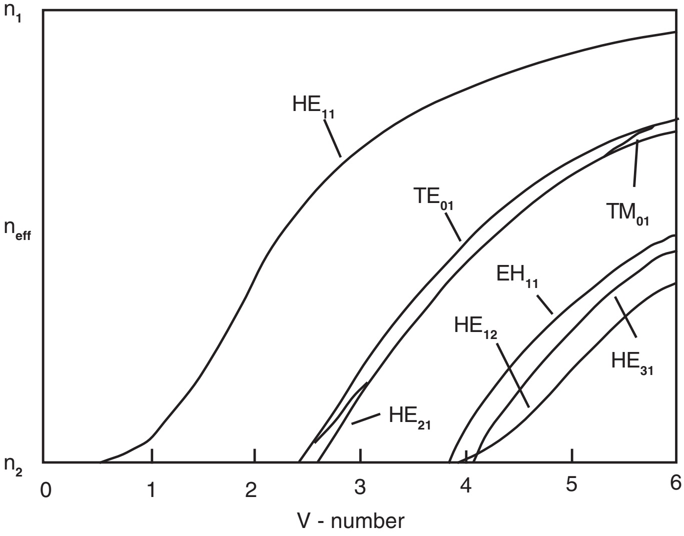
## Optical Fibers and Modes

**Optical fibers** are thin and flexible structured cylinders made from glass so pure that the fibers are a lossless transmission medium for light of an appropriate wavelength λ and for sufficiently short distances. The simplest form of an optical fiber is the **step-index fiber**, in which a core glass with an index of refraction $n_1$ is surrounded by a cladding glass of index $n_2$, where $n_1 > n_2$. Light is confined to the fiber via the process of **total internal reflection** (TIR), i.e., a beam of light is totally reflected when it impinges from the $n_1$ side of a boundary between $n_1$ and $n_2$ regions if the angle of incidence $\theta > \sin^{-1}(n_2 / n_1)$.

The propagating light solutions of Maxwell's equations for a step-index fiber identify distinct wave configurations or **modes** that can propagate in the fiber. The lowest-order allowed modes are shown below.

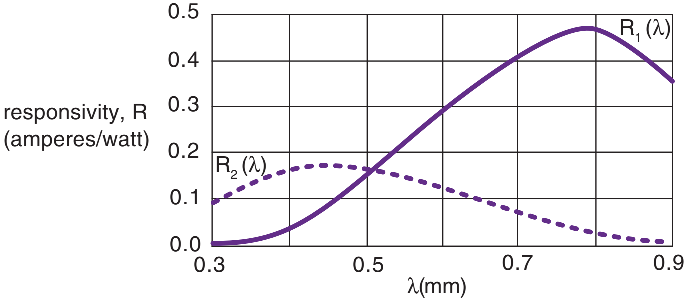


In this figure, the effective-mode index of refraction is $n_{\text{eff}} = (\beta\lambda/2\pi)$, the **V-number** is $V = (2\pi a/\lambda)\,(n_1{}^2 - n_2{}^2)^{1/2}$, the fiber core radius is $a$, and β is the mode-propagation constant. Note that this figure shows the allowed mode-propagation constants for a given core radius; for a V-number less than 2.405, only one mode can propagate.

## Color Sensors

The most common method of detecting the wavelength λ of a single **monochromatic signal** involves a spectrometer in which the optical signal is diffracted by a grating at different angles (depending on λ) and detected by either a photodiode array or a single fixed photodiode with a rotatable grating.

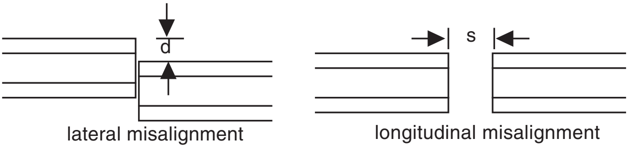
Other options include **RGB sensors**, in which three photodiodes have red, green, and blue filters in front of them. An interesting option for sensing wavelength and intensity of a single monochromatic sensor is the photodiode color sensor. When exposed to a monochromatic signal, this type of sensor, which has two stacked p-n junctions, provides two distinct outputs representing different responsivities in different regions of the photodiode. The region that is first encountered by the optical signal is more sensitive to red light [responsivity $R_1(\lambda)$], and the deeper region is more sensitive to blue light [responsivity $R_2(\lambda)$]. These responsivities for a typical device at room temperature are shown below.



For any monochromatic signal within the region between ~0.45 mm and ~0.78 mm, the difference/sum of the two detected signals will be a monotonically increasing function, thereby allowing the signal's wavelength to be uniquely determined. However, the two detector responsivites are temperature dependent. This can be compensated for by using the diode as a temperature sensor, i.e., measuring some portion of the sensor's current–voltage curve in the absence of illumination, determining the temperature, and then adjusting the responsivities.

## In-Line Fiber Coupling Theory

When the ends of two equivalent, polished multimode fibers are brought into proximity, the **coupling loss** between them can be used as a transducer mechanism. The two primary loss mechanisms used in simple fiber optic sensors depend on either axial or longitudinal displacement.



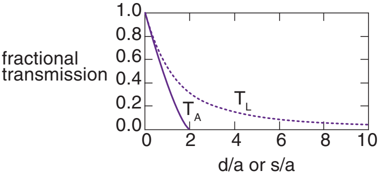
For a multimode step-index fiber with a radius $a$ and **numerical aperture** $NA = 0.37$ [where the fiber critical angle $\theta_c = \sin^{-1}(NA)$], the fractional transmission $T_A$ as a function of **axial displacement** is given by

$$T_A = \frac{2}{\pi}\cos^{-1}\left(\frac{d}{2a}\right) - \left(\frac{d}{\pi a}\right)\left[1 - \left(\frac{d}{2a}\right)^2\right]^{1/2}$$

whereas the fractional transmission $T_L$ as a function of **longitudinal displacement** is given by

$$T_L = \left[\frac{1}{1 + \left(\frac{s}{a}\right)\tan\theta_c}\right]^2$$

These fractional losses are shown in the figure below:

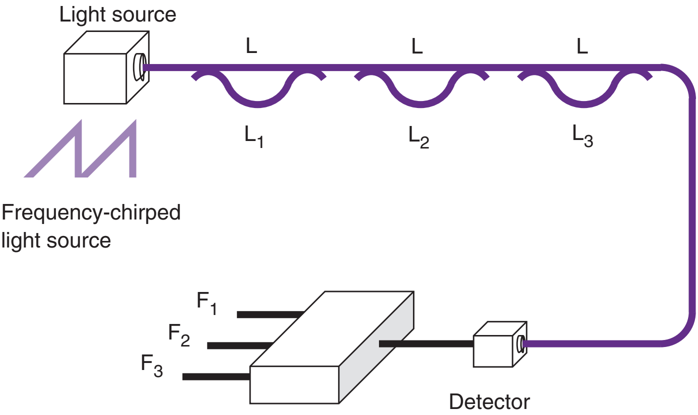


When both axial and longitudinal displacement are present, the situation becomes much more complicated.

## Frequency Division Multiplexing

**Frequency division multiplexing** (FDM) can be used effectively to support arrays of Mach–Zehnder and Michelson interferometers. In this case the light source is operated in a chirped mode where the frequency of the light output changes at $dF/dt$. By arranging each successive fiber interferometer to have a net path length difference $(L - L_m)$, the two light beams will combine after exiting the interferometer with a carrier frequency $F_m$ given by

$$F_m = (L - L_m)n/c$$

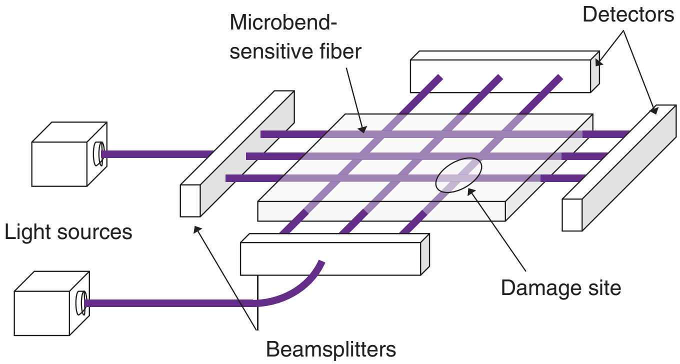


The frequency signal associated with each of the length offsets is then used to separate out each of the successive signals from the Mach–Zehnder (transmission) or Michelson (reflection) interferometers.

One key limitation of this approach is that its performance is highly dependent on the stability of the light source. In particular, if the frequency of the light source varies in a random manner, the offset between the legs of the interferometer generate corresponding **phase noise** $d\phi = 2\pi dF(L - L_m)n/c$.

## Damage-Assessment Microbend Sensor

Even the simplest fiber optic sensors can be used to support important functions. The following figure illustrates a configuration that can measure and localize damage to a structure. In this case, light sources, such as low-cost LEDs, are used to couple light into arrays of microbend-sensitive fiber that are woven into or attached to the structure. When an impact occurs that induces damage, the structure is deformed, and microbend loss changes the light level detected for that specific fiber element. By using 2D configurations, the location of the damage may be determined.



This configuration can also enable safety mats for use with dangerous machinery. Microbend-sensitive optical fibers are woven into the mat, and when an operator is too close to the machinery and steps on the mat, the signal level goes down, and the machinery is switched off. For this simple application, only one light source and detector is needed. The microbend-sensitive optical fiber is wound back and forth through the mat as a single strand.

Another variant of this approach uses metal plates with a specific period optimized for the maximum microbend response for an optical fiber design. Pressure on the plate changes the amplitude output.