530192 “Photonics in semiconductors”, (5 op / 3 ov), period III and IV – Spring 2017

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Lecture 04
Optical Fibers
Since only one mode propagates in a single mode, step-index fiber, there is no intermodal dispersion of an input light pulse.

Recall: The index of refraction depends on the wavelength of the light.

Thus there will still be dispersion due to the variation of the refractive index $n_1$ of the core glass with the wavelength of the light coupled into the fiber.

All real light sources are a range of wavelengths, even the best sources. This range may be very narrow, but there is still a limited range of wavelengths in the light source.

This type of dispersion that results from the wavelength dependence of the material properties of the guide is called material dispersion.
All excitation sources are inherently non-monochromatic and emit within a spectrum, $\Delta \lambda$, of wavelengths.

Waves in the guide with different free space wavelengths travel at different group velocities due to the wavelength dependence of $n_1$.

The waves arrive at the end of the fiber at different times and hence result in a broadened output pulse.
Even though $D_m$ may be positive or negative, the pulse broadening ($\Delta \tau$) and range of wavelength ($\Delta \lambda$) are defined as positive quantities.

For silica (SiO$_2$) the curve passes through zero at $\lambda \sim 1.27 \ \mu$m. When silica is doped with germania (GeO$_2$) to increase the refractive index of the core, the $D_m$ vs. $\lambda$ curve shifts slightly to higher wavelengths.
The waveguide dispersion, is due to the dependence of the group velocity $v_g(01)$ of the fundamental mode on the V-number, which depends of the source wavelength ($\lambda$), even if $n_1$ and $n_2$ were constant.

Waveguide dispersion arises as a result of the guiding properties of the waveguide. The energy distribution in the waveguide is a function of the radial size for the core and the wavelength propagation.

There is a non-linear frequency versus propagation constant relationship in a fiber. The result is that once again there is pulse broadening by another mechanism.

$$\frac{\Delta \tau}{L} = |D_w(\lambda)| \ast \Delta \lambda$$

where $D_w$ is defined as the waveguide dispersion coefficient.
Both waveguide and material dispersion mechanisms are based on the fundamental mode velocity depending on the source wavelength with a real source having a finite width of wavelengths.

This type of dispersion caused by a range of source wavelengths is called chromatic dispersion and includes both waveguide and material dispersion.

\[
\frac{\Delta \tau}{L} = |D_m + D_w| \Delta \lambda
\]

The chromatic dispersion is zero at around 1300 nm.

Since \( D_w \) depends on the guide geometry, it is possible to shift the zero dispersion wavelength \( \lambda_0 \) by suitably designing the guide. For example: by reducing the core radius and increasing the core doping \( \lambda_0 \) can be shifted to 1550 nm where light attenuation in the fiber is minimal. Such fibers are called dispersion shifted fibers.
Profile and Polarization Dispersion Effects

- Profile dispersion arises because the group velocity \( v_g(01) \) of the fundamental mode also depends on the refractive index difference \( \Delta \), i.e. \( \Delta = \Delta(\lambda) \). If \( \Delta \) changes with wavelength, then different wavelengths from the source would have different group velocities and experience different group delays leading to pulse broadening.

- Polarization dispersion arises when the fiber is not perfectly symmetric and homogeneous. This results in the refractive index being anisotropic.

- When the refractive index depends on the direction of the electric field, the propagation constant of a given mode depends on its polarization.

Suppose that the core refractive index has different values along two orthogonal directions corresponding to the electric field oscillation direction (polarizations). We can take \( x \) and \( y \) axes along these directions. An input light will travel along the fiber with \( E_x \) and \( E_y \) polarizations having different group velocities and hence arrive at the output at different times.
Dispersion Flattened Fibers

- Waveguide dispersion, represented by $D_w$, can be adjusted by changing the waveguide geometry.
- The refractive index profile of such a fiber looks like a W in which the cladding is a thin layer with a depressed refractive index; the fiber is called *doubly clad*.

Dispersion flattened fiber example. The **material dispersion coefficient** ($D_m$) for the core material and **waveguide dispersion coefficient** ($D_w$) for the doubly clad fiber result in a flattened small chromatic dispersion between $\lambda_1$ and $\lambda_2$. 
In digital communications, signals are generally sent as light pulses along an optical fiber.

We must know the maximum rate at which the digital data can be transmitted along the fiber. This rate is called the bit rate capacity $B$ (bits per second) of the fiber and is directly related to the dispersion characteristics.
Bit rate

- Dispersion (pulse broadening) is typically measured between the half-power points (FWHM) of the arriving signal.
- A light pulse travels down a fiber of length L in time t and suffers a spread $\Delta \tau$ in arrival times of the different guided waves.
- If the spread in time is $\Delta \tau$ measured at FWHM then the condition of NO intersymbol interference demands that the pulses must be time separated by no less than $2 \Delta \tau$.
- Thus we can feed in pulses at the input, at best, at every $2 \Delta \tau$ seconds which then defines the period (T) of the input pulses.
- The maximum bit rate (the number of bits that are conveyed or processed per unit of time) $B$ is then:

$$B \approx \frac{1}{2\Delta \tau}$$

This is very rough and only a qualitative guess.

Additionally, the diagram illustrates the input and output intensity over time for very short light pulses. The input is shown with a very short pulse at time $T$, and the output shows a spread in arrival times $\Delta \tau_{1/2}$, with a total spread of $\sim 2\Delta \tau_{1/2}$. The intensity is plotted against time.
Return to Zero (RZ) bit rate or data rate. If the signal must return to zero before the start of the next pulse, the data train is called a return to zero format. The pulse occupies only half of the total period \( T \) of the bit.

The Bit rate is then as shown by the equation:

\[
B \approx \frac{1}{2\Delta \tau}
\]
Non-Return to Zero

Non-return to zero (NRZ) bit rate. If the signal is allowed to occupy the entire width of the period, it is called a non-return to zero format. Thus the bit rate becomes

$$B \approx \frac{1}{\Delta \tau}$$

While this seems advantageous, nothing is free. The lost of an inherent clocking component to the signal as well as DC level shifting and other coding effects can erode this method’s advantage.
We can drive the emitter using a sinusoidal signal.

An optical fiber link for transmitting analog signals and the effect of dispersion in the fiber on the bandwidth, $f_{\text{op}}$.

We would like to find the relation between electrical and optical bandwidth.
The light output should have the same intensity for the various modulation frequencies. But as the modulation frequency increases, there is a point where the total dispersion “smears” the light pulse at the detected end.

Now the output intensity no longer resembles the input accurately.

Thus $f_{op}$ is defined as the frequency where

$$P_{input}/P_{output} = 1/2$$

Intuitively, the optical cut-off frequency $f_{op}$ should correspond roughly to the bit rate, $=> f_{op} = B$.

For a Gaussian shaped pulse

$$f_{op} \approx 0,75B \text{(bandwidth)}$$
The received signal (either voltage or current) bandwidth is measured at the power point where the signal is 70.7% of its low frequency value.

The exact relationship between $f_{el}$ and $f_{op}$ (bandwidth) depends on the dispersion through the fiber. This dispersion will "shift" the intensity which may both increase the chance of intersymbol interference and modify the resulting detected intensity.

If the fiber dispersion characteristics are Gaussian, then $f_{el} \approx 0.71 \times f_{op}$
By tailoring the index of refraction of the core/cladding, we can nearly equalize the arrival times for many modes.

(a) Multimode step index fiber. Ray paths are different so that rays arrive at different times.

(b) Graded index fiber. Ray paths are different but so are the velocities along the paths so that all the rays arrive at the same time.
Gradient Index Fiber

The ray path is bent continuously until TIR is achieved.

(a) A ray in thinly stratified medium becomes refracted as it passes from one layer to the next upper layer with lower $n$ and eventually its angle satisfies TIR.

(b) In a medium where $n$ decreases continuously the path of the ray bends continuously.

The refractive index profile can generally be described by a power law with an index $\gamma$ called the profile index (or the coefficient of index grating) so that,

\[
\begin{align*}
n &= n_1[1 - 2\Delta(r/a)^{\gamma}]^{1/2} ; r < a, \\
n &= n_2 ; r = a
\end{align*}
\]
Step Model of a GRIN Fiber

AXIS

CORE

CLADDING

2a

CORE
The refractive index profile can generally be described by a power law with an index $\gamma$ called the **profile index** (or the **coefficient of index grating**) so that,

$$n = n_1 [1 - 2 \Delta (r/a)^\gamma]^{1/2} \quad ; \quad r < a,$$

$$n = n_2 \quad ; \quad r = a$$

Minimum intermodal dispersion

$$\gamma_o \approx 2 + \delta - \Delta \frac{(4 + \delta)(3 + \delta)}{5 + 2\delta} \approx 2$$

- Bandwidth ranges from 100MHz-Km to 1GHz-Km
- Bandwidth range 20-30 MHz for multimode step index fiber
### Fiber Comparison

<table>
<thead>
<tr>
<th>Property</th>
<th>Multimode step-index fiber</th>
<th>Single-mode step-index fiber</th>
<th>Graded index fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta = (n_1 - n_2)/n_1$</td>
<td>0.02</td>
<td>0.003</td>
<td>0.015</td>
</tr>
<tr>
<td>Core diameter (μm)</td>
<td>100</td>
<td>8.3 (MFD = 9.3 μm)</td>
<td>62.5</td>
</tr>
<tr>
<td>Cladding diameter (μm)</td>
<td>140</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>NA</td>
<td>0.3</td>
<td>0.1</td>
<td>0.26</td>
</tr>
<tr>
<td>Bandwidth × distance or Dispersion</td>
<td>20 – 100 MHz km.</td>
<td>&lt;3.5 ps km⁻¹ nm⁻¹ at 1.3 μm</td>
<td>300 MHz km – 3 GHz km at 1.3 μm</td>
</tr>
<tr>
<td>Attenuation of light</td>
<td>4 – 6 dB km⁻¹ at 850 nm</td>
<td>1.8 dB km⁻¹ at 850 nm</td>
<td>3 dB km⁻¹ at 850 nm</td>
</tr>
<tr>
<td></td>
<td>0.7 – 1 dB km⁻¹ at 1.3 μm</td>
<td>0.34 dB km⁻¹ at 1.3 μm</td>
<td>0.6 – 1 dB km⁻¹ at 1.3 μm</td>
</tr>
<tr>
<td>Typical light source</td>
<td>Light emitting diode (LED)</td>
<td>Lasers, single mode injection lasers</td>
<td>LED, lasers</td>
</tr>
<tr>
<td>Typical applications</td>
<td>Short haul or subscriber local network communications</td>
<td>Long haul communications</td>
<td>Local and wide-area networks, Medium haul communications</td>
</tr>
</tbody>
</table>
In general, when light propagates through a material it becomes attenuated in the direction of propagation.

We distinguish between absorption and scattering, both of which give rise to a loss of intensity in the regular direction of propagation.

In addition, extrinsic factors such as fiber bending can also lead to light attenuation.

\[ \text{Attenuation} = \text{Absorption} + \text{Scattering} \]

**Attenuation coefficient** \( \alpha \) is defined as the *fractional decrease in the optical power per unit distance*. \( \alpha \) is in \( \text{m}^{-1} \).

\[ P_{\text{out}} = P_{\text{in}} \exp(-\alpha L) \]
In absorption, some of the energy of the propagating wave is converted to other forms of energy, e.g. heat by the generation of lattice vibrations.

Lattice absorption: The solid in the example is made of ions and as an EM wave propagates it displaces the oppositely charged ions in opposite directions and forces them to vibrate at the frequency of the wave - the medium experiences ionic polarization.

Lattice absorption through a crystal. The field in the wave oscillates the ions which consequently generate "mechanical" waves in the crystal; energy is thereby transferred from the wave to lattice vibrations.
Absorption

The ions and hence the lattice is made to vibrate by the passing EM wave, some energy is coupled into the lattice vibrations of the solid. The energy has maximum when the frequency of the wave is close to the natural lattice vibrational frequencies.

Typically, these frequencies are in the infrared region. Most of the energy is then absorbed from the EM wave and converted to lattice vibrational energy (heat).

Energy from a passing EM wave can also be absorbed by various ionic impurities in a medium, as these charges can couple to the electric field and oscillate.
Scattering

When light encounters matter, matter not only re-emits light in the forward direction (leading to absorption), but it also re-emits light in all other directions. This is called scattering.

The incident plane wave, sweeps across an atom and spherical wavelets are scattered. The process is continuous, and hundreds of millions of photons per second stream out of the scattering atom in all directions.
Rayleigh Scattering

- Rayleigh scattering – particle size about 1/10 of the wavelength
- Short wavelengths scatter more!

- Elastic (\(\lambda\) does not change)
- Random direction of emission
- Little energy loss

\[ \beta_T = \text{isothermal compressibility (at } T_f) \]

\[ T_f = \text{fictive temperature (roughly the softening temperature of glass)} \text{ where the liquid structure during the cooling of the fiber is frozen to become the glass structure} \]

The field forces dipole oscillations in the particle (by polarizing it) which leads to the emission of EM waves in "many" directions so that a portion of the light energy is directed away from the incident beam.

\[ \alpha_R \approx \frac{8\pi^3}{3\lambda^4} \left(n^2 - 1\right)^2 \beta_T k_B T_f \]
Light Ray Scattering

Rayleigh scattering of waves in a medium arises whenever there are small inhomogeneous regions in which the refractive index is different than the medium (which has some average refractive index). This means a local change in the relative permittivity and polarizability. The result is that the small inhomogeneous region acts like a small dielectric particle and scatters the propagating wave in different directions.
Definitions of (a) microbending and (b) macrobending loss and the definition of the radius of curvature, $R$. $D$ is the fiber diameter, including the cladding.

The propagating mode in the fiber is shown as white painted area. Some radiation is lost in the region where the fiber is bent.
Bending Losses

Sharp bends change the local waveguide geometry that can lead to waves escaping. The zigzagging ray suddenly finds itself with an incidence angle $\theta'$ that gives rise to either a transmitted wave, or to a greater cladding penetration; the field reaches the outside medium and some light energy is lost.
Bending Losses
Macro-bending Losses

- **Macro-bending losses** – the radius of curvature $R$ of the bend is comparable to the diameter of the fiber - much greater than 1 mm
- Typically occur when the fiber is bent during the installation of a fiber optic link such as turning the fiber around a corner.
- There is no simple precise and sharp boundary line between micro-bending and macro-bending loss definitions.
- Both losses have essentially resulted from changes in the waveguide geometry and properties as the fiber is subjected to external forces that bend the fiber.
Micro-bending Losses

- Micro-bending losses – the radius of curvature $R$ of the bend is sharp and bend radius is comparable to the diameter of the fiber. Typically microbending losses are significant when the radius of curvature of the bend is less than 0.1 - 1 mm.

- They can arise from:
  - Careless or poor cabling of the fiber
  - Or even in flaws in manufacturing that result in variations in the fiber geometry over small distances.
  - Strain on the fiber cables changes the index of refraction.

- During installation, care must be taken to avoid unnecessary strains and bends in the fiber for telecommunications applications.
Bend Insensitive Fibers

(a) Bending loss in dB per turn of fiber for three types of fibers, standard single mode, and two trench fibers, around 1.55 - 1.65 μm. (b) The index profile for the trench fiber 1 in (a), and a schematic view of the fiber cross section. Experimental data have been used to generate the plots have been combined from various sources. (Standard fiber, M.-J. Li et al. J. Light Wave Technol., 27, 376, 2009; trench fiber 1, K. Himeno et al, J. Light Wave Technol., 23, 3494, 2005, trench fiber 2, L.-A. de Montmorillon, et al. “Bend-Optimized G.652D Compatible Trench-Assisted Single-Mode Fibers”, Proceedings of the 55th IWCS/Focus, pp. 342-347, November, 2006.)
Bend Insensitive Fibers

Left, the basic structure of bend insensitive fiber with a nanoengineered ring in the cladding. Right, an SEM picture of the cross section of a nanoengineered fiber with reduced bending losses. (Courtesy of Ming-Jun Li, Corning Inc. For more information see US Patent 8,055.110, 2011)
As light propagates through an optical fiber it becomes **attenuated** by a number of processes that depend on the **wavelength** of light.

The **attenuation coefficient** \( \alpha \) is defined as the **fractional decrease** in the optical power per unit distance

\[
\alpha = -\frac{1}{P} \frac{dP}{dx}
\]

The attenuation coefficient is usually calculated from the **ratio** of the input power \((P_{in})\) and received power \((P_{out})\) - detected at the output of the fiber.

\[
\alpha = \frac{1}{L} \ln\left(\frac{P_{in}}{P_{out}}\right)
\]
Attenuation in Optical Fibers

The power at the output of the fiber is then

\[ P_{out} = P_{in} \exp(-\alpha L) \]

We usually state the attenuation in terms of dB per kilometre.

\[ \alpha_{dB} = \frac{1}{L} 10 \log\left( \frac{P_{in}}{P_{out}} \right) = 4.43 \alpha \]
Absorption & Scattering Losses in Fibers

Two types of absorption exist:
- **Intrinsic Absorption**, caused by interaction with one or more of the components of the glass
- **Extrinsic Absorption**, caused by impurities within the glass
Intrinsic Absorption Losses in Fibers

- Intrinsic absorption in the ultraviolet region is caused by electronic absorption bands.
- The main cause of intrinsic absorption in the infrared region is the characteristic vibration frequency of atomic bonds. In silica glass, absorption is caused by the vibration of silicon-oxygen (Si-O) bonds. The interaction between the vibrating bond and the electromagnetic field of the optical signal causes intrinsic absorption. Light energy is transferred from the electromagnetic field to the bond.

Attenuation spectrum of pure silica glass.

Intrinsic absorption is very low compared to other forms of loss.
Extrinsic Absorption (Metallic Ions)

- Extrinsic absorption is much more significant than intrinsic
- Caused by impurities introduced into the fiber material during manufacture
  - Iron, nickel, and chromium
- Caused by transition of metal ions to a higher energy level
- Modern fabrication techniques can reduce impurity levels below 1 part in $10^{10}$.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Peak wavelength (nm)</th>
<th>One part in $10^9$ (dB km$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr$^{3+}$</td>
<td>625</td>
<td>1.6</td>
</tr>
<tr>
<td>C$^{2+}$</td>
<td>685</td>
<td>0.1</td>
</tr>
<tr>
<td>Cu$^{2+}$</td>
<td>850</td>
<td>1.1</td>
</tr>
<tr>
<td>Fe$^{2+}$</td>
<td>1100</td>
<td>0.68</td>
</tr>
<tr>
<td>Fe$^{3+}$</td>
<td>400</td>
<td>0.15</td>
</tr>
<tr>
<td>Ni$^{2+}$</td>
<td>650</td>
<td>0.1</td>
</tr>
<tr>
<td>Mn$^{3+}$</td>
<td>460</td>
<td>0.2</td>
</tr>
<tr>
<td>V$^{4+}$</td>
<td>725</td>
<td>2.7</td>
</tr>
</tbody>
</table>

For some of the more common metallic impurities in silica fiber the table shows the peak attenuation wavelength and the attenuation (dB/km) caused by an impurity concentration of 1 in $10^9$. 
Extrinsic Absorption (OH Ions)

- Extrinsic absorption caused by dissolved water in the glass, as the hydroxyl or OH ion.
- In this case absorption due to the same fundamental processes (between 2700 nm and 4200 nm) gives rise to so-called absorption overtones at 1380, 950, and 720 nm.
- Typically a 1 part per million impurity level causes 1 dB/km of attenuation at 950 nm. Typical levels are a few parts per billion.

Absorption Spectrum for OH in Silica
For 1550 nm the loss is approximately 0.18 dB per km.

• Rayleigh Scattering Losses - dominant scattering mechanism in silica fibers
  • Scattering causes by inhomogeneities in the glass, of a size smaller than the wavelength.
  • Inhomogeneities manifested as refractive index variations, present in the glass after manufacture.
  • Difficult to eliminate with present manufacturing methods
Attenuation falls with increasing wavelength, so that the loss at 1550 nm is only about 0.25 dB/km, compared to about 2.5 dB/km at 850 nm.

- Three low loss transmission windows exist circa 850, 1320, 1550 nm
- Earliest systems worked at 850 nm, the latest systems at 1550 nm.
1. A core, having high refractive index.
2. Cladding.
3. Buffer, protective polymer layer.
4. Jacket, protective polymer layer.
1965: Kao and Hockham proposed fibers for broadband communication

1970s: commercial methods of producing low-loss fibers by Corning and AT&T.

1990: single-mode fiber, capacity 622 Mbit/s
Chemical Vapor Deposition (CVD) is chemical reactions which transform gaseous molecules, called precursor, into a solid material, in the form of thin film or powder, on the surface of a substrate.
Decomposition of Precursor and Incorporation into Solid Films
1. The method was developed by Bell Laboratories.
2. The gaseous mixture of reactants is fed at the end of a rotating silica tube.
3. This tube is heated by a traversing oxygen-hydrogen burner.
4. As a result of chemical reactions glass particles, called soot, are formed and deposited on the internal wall of the tube.
5. The soot is then vitrified by the traversing burner to provide a thin glass layer.
6. The process is repeated many times as the cladding layers and core layers are formed.
7. When the deposition is finished, the temperature of the burner is increased to collapse the tube into a solid preform.
Outside Vapor Deposition (OVD)

Donald Keck, Bob Maurer and Peter Schultz (left to right) at Corning shortly after announcing the first low loss optical fibers made in 1970. Keck, Maurer and Schultz developed the outside vapor deposition (OVD) method for the fabrication of preforms that are used in drawing fibers with low losses. Their OVD was based on Franklin Hyde’s vapor deposition process developed earlier at Corning in 1930s. OVD is still used today at Corning in manufacturing low loss fibers. (Courtesy of Corning)
Outside Vapor Deposition (OVD)

1. The process was exclusively used by Corning since the 1970s, and the patent on such a technology has expired since July 2000.
2. Halogens and $O_2$ react in a hot flame to form hot glass soot, which is deposited layer by layer on an aluminium oxide or graphite mandrel.
3. The central mandrel is removed after deposition.
4. In the last step, called sintering, a hollow porous preform is dehydrated and collapsed in controlled atmosphere, (e.g. helium) to form desired preform.
1. In VAD method, the preform can be fabricated **continuously**.
2. Starting chemicals are carried from the bottom into **oxygen-hydrogen burner** flame to produce glass **soot** which is deposited at the end of a **rotating silica rod**.
3. A porous preform is then grown in the **axial** direction.
4. The starting rod is **pulled upward and rotated** in the same way as that used to grow single crystals.
5. Finally the preform is **dehydrated** and **vitrified** in ring heaters.
6. This process is preferred for the mass production.
1. The drawing process is **integrated** with the coating process to avoid contamination of fiber surface.
2. The tip of the perform is **heated** in a furnace to a molten state.
3. Formed molten gob falls down under the **force of gravity** while shrinking in diameter into a proper diameter strand.
4. It is controlled continuously during the drawing process.
5. Fiber diameter drift cannot exceed 0.1%.
6. The strand is threaded through a series coating applicators immediately after drawing.
7. Liquid prepolymer coatings are cured by thermal or ultraviolet apparatus.
8. Dual coating, soft inner and hard outer, is needed to avoid microbending and protect against impact and crushing forces in either manufacturing process or installation.
9. The fiber with coatings is pulled down and wound on a winding drum.
10. The drawing process must take place in an air conditioned room (clean room), because air pollution influences fiber attenuation.
Global Undersea Fiber Systems

Optical fibre submarine systems
Light is guided along a water jet as demonstrated by Jean-Daniel Colladon.
First demonstration was around 1841.
This illustration was published in La Nature, Revue des Sciences, in 1884 (p. 325). (Comptes Rendes, 15, 800-802, Oct. 24, 1842).
A similar demonstration was done by John Tyndall for the Royal Institution in London in his 1854 lecture. Apparently, Michael Faraday had originally suggested the experiment to John Tyndall though Faraday himself probably learned about it either from another earlier demonstration or through Jean-Daniel Colladon's publication.
Although John Tyndall is often credited with the original discovery of a water-jet guiding light, Tyndall, himself, does not make that claim but neither does he attribute it to someone else.
Charles Kao and his colleagues carried out the early experiments on optical fibers at the Standard Telecommunications Laboratories Ltd (the research center of Standard Telephones and Cables) at Harlow in the United Kingdom, during the 1960s. He shared the Nobel Prize in 2009 in Physics with Willard Boyle and George Smith for "groundbreaking achievements concerning the transmission of light in fibers for optical communication."

In a milestone paper with George Hockam published in the IEE Proceedings in 1966 they predicted that the intrinsic losses of glass optical fibers could be much lower than 20 dB/km, which would allow their use in long distance telecommunications.

Today, optical fibers are used not only in telecommunications but also in various other technologies such as instrumentation and sensing.

From 1987 to his retirement in 1996, professor Kao was the Vice Chancellor of the Chinese University of Hong Kong.