Transmission of Light in Fiber for Optical Communication

Mrs. Gwen MW Kao
on behalf of
Professor Charles K Kao
Nobel Laureate in Physics 2009

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Aula Magna
Stockholm University
Sand from centuries past; Send future voices fast.
Early years
STL building in 1960’s

Now called Kao-Hockham Building in Harlow, Essex, UK
Low-loss corrugated circular waveguide

Young Kao at workplace
Laser invented

1917: Einstein postulated stimulated emission
1953: Townes, Gordon, and Zeiger demonstrated Maser
1958: Townes and Schawlow invented Laser

Charles H. Townes
Arthur L. Schawlow

http://www.bell-labs.com/history/laser/invention/
A race between mm waveguide and optical communication

<table>
<thead>
<tr>
<th>Millimeter Waveguide</th>
<th>Optical Communication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mature technology</td>
<td>Unknown technology</td>
</tr>
<tr>
<td>Ready for deployment</td>
<td>Promising but nothing is sure</td>
</tr>
<tr>
<td>Expensive</td>
<td>Potentially low cost</td>
</tr>
<tr>
<td>Phone monopoly can afford the cost</td>
<td>Who are the investors?</td>
</tr>
<tr>
<td>Moderate capacity improvement</td>
<td>100,000X better</td>
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</tbody>
</table>

Odds favored the matured millimeter wave technology
Two key questions raised by Prof Kao

1. *Is Ruby laser a suitable source for optical communication?*

2. *What material has sufficiently high transparency at such wavelengths?*

Difficult problems but fortune favors the brave!
Free space optical communications

Laser flickers in free space!
A waveguide needed.

Con-focal lens system

Alignment of the lenses is critical!
Thermal gradient can cause beam to shift by many cm


Gas lens system

Difficult to insulate!

Hollow metallic and dielectric waveguides

Large bending loss and expensive

Thin film waveguide

a. A thin film waveguide surrounded by supporting material

b. Field structure of guided wave

Confinement not strong enough and light escapes in bends

Prof Kao’s team pursued dielectric silica waveguide approach

- **Problems to be solved**
  - *Loss reduction* in dielectric waveguide materials
  - *Physical and waveguide limitations* for glass fiber
  - **Better light source** needs
    - a semiconductor laser in the near infrared
    - emission characteristics matching the diameter of a single mode fiber
    - durability and can work at room temperatures
  - **Measurement of the optical loss** of highly transparent materials
Optical loss of transparent materials

- **Intrinsic loss** in the materials itself (infrared absorption)
- **Extrinsic loss** due to impurity ions
- **Rayleigh scattering loss** due to structure non-uniformity

Is silica glass a suitable material? But all experts said its loss is too high!
What needs to be done

- **Impurities**, particularly transition elements such as iron, copper, manganese, **have to be reduced** to parts per million or even parts per billion.

- **High temperature glasses** are frozen rapidly and are more homogeneous, leading to a lower scattering loss.
The 1966 paper

Dielectric-fibre surface waveguides for optical frequencies


Synopsis

A dielectric fibre with a refractive index higher than its surrounding region is a form of dielectric waveguide which represents a possible medium for the guided transmission of energy at optical frequencies. The particular type of dielectric-fibre waveguide discussed is one with a circular cross-section. The choice of the mode of propagation for a fibre waveguide used for communication purposes is governed by consideration of loss characteristics and information capacity. Dielectric loss, bending loss and radiation loss are discussed, and mode stability, dispersion and power handling are examined with respect to information capacity. Physical-realisation aspects are also discussed. Experimental investigations at both optical and microwave wavelengths are included.

PROC. IEE, Vol. 113, No. 7, JULY 1966

The birthday of optical fiber communication
Waveguide design

The following form of optical waveguide has a larger information capacity and possible advantages in basic material cost.

- A fiber of glassy material in a cladded structure
- Core diameter $\sim \lambda_0$
- Overall diameter $\sim 100 \lambda_0$
- Refractive index of the core $\sim 1\%$ higher than the cladding.
- Single $\text{HE}_{11}$, $\text{E}_0$ or $\text{H}_0$ mode operation
- Information capacity in excess of 1 Gc/s. ...
Detailed analysis of fiber losses

Intrinsic loss can be as low as 1 dB/km!

Radiation loss

Attenuation of PMMA

Bending loss
Main points of the 1966 paper

- Loss can be reduced if the **mode** is properly chosen;
- Proposal for a fiber surrounded by a **cladding** of lower index - became the standard technology;
- Negligible energy loss due to **fiber bends** larger than 1 mm;
- Estimation of fiber losses for **non-uniform** cross-section;
- Analysis of the **properties** of a single mode fiber;
- Bandwidth limited by **dispersion**.
Conclusions of the 1966 paper

- The realization of a successful fiber waveguide depends, at present, on the availability of suitable low-loss dielectric material. The crucial material problem appears to be one which is difficult but not impossible.

- Certainly, the required loss figure of around 20 dB/km is much higher than the lower limit of loss figure imposed by fundamental mechanisms.
In hindsight, the revolutionary conclusion was too conservative.

To date, loss is $1/100$ as predicted, bandwidth is $10,000$ times predicted!
Prof Kao travelled to convince the world

At an early OFC meeting

Science Museum
South Kensington, London
Measurement problems

- Two formidable challenges
  - A sample size only ~ 20 cm – difficult to measure low-loss
  - End surface reflection loss could be an order of magnitude higher than the actual loss
Measurement of fiber loss

- Loss too low to measure
- Built a double beam spectrophotometer to improve sensitivity by 10X!
- The surface effect was characterized by a homemade ellipsometer.

Demonstration of silica glass as waveguide material

- An Infrasil sample from Schott Glass showed an attenuation as low as 5 dB/km at a window around 850 nm!
- 850 nm - GaAs laser emission region.

The race to develop the first low-loss optical fiber

Outside Vapor Deposition Method used by Corning in 1970

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Fiber drawing

- Many optical fiber production methods invented
  - OVD
  - VAD
  - MCVD
  - PCVD

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Light guiding inside fiber

Snell’s Law: \[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

Note: if we increase \( \theta_1 \) to \( \theta_c \) such that \( \theta_2 = 90^\circ \)

\[ \sin \theta_c = \frac{n_2}{n_1}, \quad n_2 < n_1 \]

If \( \theta_1 > \theta_c \)

\[ \rightarrow \quad \text{Total Internal Reflection} \]
High-capacity experimental demonstration

15.5 Terabits/sec capacity
- 155 wavelengths
- 100 Gbps each
- over 7000 km

Hundreds of millions of km of fiber cables deployed
New industries created
Submarine fiber optic systems

Over 420,000 km of fiber in over 100 undersea fiber optic systems are deployed.

Courtesy: JX Cai, Tyco Telecommunications
Global fiber deployment (million km)

Other S-M = utility, railway, highway, government, military, premises, etc.
Other local tel. = CO trunks, metro rings, business/office parks, CLEC, etc.

Source: KMI Research, CRU Group

The Chinese University of Hong Kong
Telecomm service life cycle

Penetration

Time

1850 1950 1990

Telegraph
Telex
Facsimile
Telephone
Video
When will fiber become obsolete?

- “I cannot think of anything that can replace fiber optics.”
- “In the next 1000 years, I can’t think of a better system.”
- “But don’t believe what I say, because I didn’t believe what experts said either.”

Courtesy of Radio Television Hong Kong
Fiber around the globe
Acknowledgement

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