Course Outline

Lecturer: Prof. CHOW Chi Wai (鄒志偉)
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TA: Mr. C. W. Hsu (許勁崴)
Email: dicky0812@gmail.com

Course homepage:
http://web.it.nctu.edu.tw/~cwchow/schedule.htm

Course assessment:
60% Project (Presentation + PPT) & 40% Final Exam

Office hours: Every Thursday 4:00pm to 6:00pm or by appointment
Course Objectives

• The goal is to provide students a basic to advanced understanding in the elements of optical communication (Fibre, Tx, Rx, amplifier, networks)

• To provide an overview of what is new and important in photonics for broadband telecommunications (rather than using difficult equation, terminology and background principle is more important)

• Possible topics to be covered include advanced issues and new directions in R and D on optical communications device and component technologies, as well as systems applications
<table>
<thead>
<tr>
<th>單元主題</th>
<th>內容要証</th>
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<tbody>
<tr>
<td>Introduction</td>
<td>Evolution of optical fiber communications</td>
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</tbody>
</table>
| Optical Fiber | 1. Fiber modes  
                   2. Fiber dispersion,  
                   3. Fiber propagation  
                   4. Fiber nonlinearities |
| Optical Transmitter | 1. Lasers  
                   2. Laser rate equation  
                   3. Lasers dynamics  
                   4. Lasers noise  
                   5. Single mode lasers (DFB, DBR)  
                   6. Direct modulation  
                   7. External modulation (Lithium Niobate modulators and Electro-absorption modulators) |
| Optical Receiver | 1. Photo-detector  
                   2. 3R receiver (re-shaping, re-timing and re-amplification)  
                   3. Receiver design  
                   4. Receiver noise  
                   5. Receiver sensitivity (Q and BER analysis)  
                   6. Sensitivity degradation |
| Optical Amplifier | 1. Semiconductor optical amplifier  
                   2. Raman amplifier and OPA  
                   3. Erbium-doped fiber amplifiers (EDFAs) |
| Optical Network | 1. WDM and OTDM networks  
                   2. Passive optical networks  
                   3. Label controlled packet switched networks  
                   4. Radio over Fiber networks |
Possible Topics for Project

1. Nonlinear optical transmission limitations in long-haul high-capacity DWDM systems
2. Wideband chromatic dispersion-compensation techniques
3. Polarization mode dispersion (PMD) compensation techniques
4. Optical amplifiers such as EDFA, SOA and Raman amplifiers
5. All-optical signal processing
Possible Topics for Project

6. Tunable lasers for DWDM systems and reconfigurable networks
7. High-nonlinearity photonic crystal fibers
8. OADMs and ROADMs (reconfigurable optical add-drop multiplexers)
9. MEM devices and potential roles in optical fiber communications systems
10. Optical buffering
11. Optical packet switched network
12. Advanced optical modulation format for spectral efficient optical networks
Possible Topics for Project

13. Gain equalization techniques and dynamic gain equalizers
14. Fiber-to-the-home (FTTH) and passive optical network (PON) technologies
15. Silicon-on-insulator (SOI) devices for optical communication (Si-Photonics)
16. Photonic devices using silicon or graphene
17. Terabit capacity transmission technologies
18. Radio-over-fiber (ROF) network architectures
19. Free space optical wireless and visible light communication (VLC) systems
20. Multicore or multimode spatial multiplexing
Text and Reference Book

Text

• 光纖通訊 – 鄒志偉，五南文化出版
• Fiber Optic Communications, Fundamentals and Applications, S. Kumar & M. J. Deen, Wiley
References

• Journal
  – JLT, JSTQE, PTL, PJ (IEEE)
    http://ieeexplore.ieee.org
  – Optics Letters, Optics Express (OSA)
    http://www.osa.org/
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Advances in Optical Fiber Communication

- **System capacity (bit-rate)**
  (as reported at OFC, a major international conference):
  - OFC 1977 ~ 45 Mb/s (0.045 Gb/s)
  - OFC 2001 ~ 10 Tb/s (10,000 Gb/s)
  - OFC 2010 ~ 69.1 Tb/s
  - OFC 2011 ~ 101.7 Tb/s
  - OFC 2012 ~ 305 Tb/s
  ~ 220,000 times increase in capacity in ~ 24 years
  ~ 1,540,000 times increase in capacity in ~ 33 years
  ~ 2,260,000 times increase in capacity in ~ 34 years
  ~ 6,800,000 times increase in capacity in ~ 35 years

- **System bit-rate-distance** (as reported at OFC):
  - OFC 1979 -- 100 Mb/s over 50 km MM fiber, with 850 nm LD
  - OFC 2002 -- 2.56 Tb/s (256 Ch. DWDM x10 Gb/s), 11,000 km SMFs+DCFs, over 80 nm in the 1550 nm region with hybrid Raman/EDFA optical amplifiers
  - OFC 2010 -- 101.8 Pbit/s•km (9.6 Tb/s x 10,608 km)
  ~ 5,600,000 times increase in bit-rate-distance in ~ 23 years
  ~ 226,000,000 times increase in bit-rate-distance in ~ 33 years
Optoelectronic Devices and Passive Components

(for 1st generation optical fiber communication systems, e.g., 1977)

- **Active Devices**
  - Laser Diodes, LEDs
  - Photodetectors (PIN, APD)

- **Passive Components**
  - Connectors, Splices
  - Couplers, Splitters, Taps, Branching Components
  - Isolators, Attenuators
Optoelectronic Devices and Passive Components

(for DWDM fiber communication systems and networks, 2011)

• Active Devices
  – Laser Diodes, LEDs
  – Photodetectors (PIN, APD)
  – Optical Amplifiers (EDFA, SOA, Raman Amplifiers, OPA)
  – Tunable Lasers, Laser Arrays
  – External Modulators, Optical Switches
  – Wavelength Routers, OXCs, Wavelength Converters
  – Electronic Processing, FPGA

• Passive Components
  – Connectors, Splices
  – Couplers, Splitters, Taps, Branching Components
  – Isolators, Attenuators
  – DWDM Mux/Dmux, Inter-leavers, Fixed/Tunable Filters
  – Optical Add-Drop Multiplexers (OADM)
  – Dispersion and Dispersion-Slope Compensators
  – Gain Flattening Filters and Dynamic Gain Equalizers
Why we need optical communication?
The Zettabyte Era: Trends and Analysis

Trend 1: Device Transitions Alter Network Demand or Use

Globally, devices and connections (10.7 percent CAGR) are growing faster than both the population (1.1 percent CAGR) and Internet users (9.2 percent CAGR). See Figure 2. This trend is accelerating the increase in the average number of devices and connections per household and per Internet user. Each year, various new devices in different form factors with increased capabilities and intelligence are introduced and adopted in the market. A growing number of M2M applications, such as smart meters, video surveillance, healthcare monitoring, transportation, and package or asset tracking, also are causing connection growth.

![Graph showing Billion of Devices (2013-2018)]

Source: Cisco Visual Networking Index, 2014

*The percentages in parentheses next to the legend denote the device share for the years 2013 and 2018, respectively.*
The Zettabyte Era: Trends and Analysis

Exabytes per Month

21% CAGR 2013-2018

- Non-Smartphones (0.1%, 0.1%)
- Other Portable Devices (0.1%, 0.4%)
- M2M (0.4%, 2.8%)
- Tablets (2.2%, 14.0%)
- Smartphones (3.5%, 16.3%)
- TVs (26.5%, 23.6%)
- PCs (67.2%, 42.8%)

Source: Cisco VNI, 2014
The percentages in parentheses next to the legend denote the device traffic shares for the years 2013 and 2018, respectively.
So why we need optical communication?
Optical Fiber Communications

• Impact of such contributions on human society is indeed highly significant…
• Just a few examples:
  – Cheap long-distance and international telephone calls
  – E-mails replacing physical mails
  – 100-channel CATV and digital cable VOD to the home
  – World-wide Internet Access, with unlimited Digital Libraries
  – Global information infrastructure for business applications
  – Global E-commerce
  – Multimedia E-mails with Photo Images, Audio and Video
  – “Free” real-time “Video Phones” over the Internet
  – HDTV
  – 3D-HDTV
  – Tele-medicine
  – ………
• All are positive Impact of Optical Fiber Communications
Elements in Optical Communication

Transmitter (Tx), Medium, Receiver (Rx)

Basical Principles
1. Converts an electrical signal to an infrared light signal
2. Launches or transmits this light signal into an optical fiber
3. Captures the signal and reconverts it to an electrical signal
The Nobel Prize in Physics 2009 was divided, one half awarded to Charles K. Kao for groundbreaking achievements concerning the transmission of light in fibers for optical communication; the other half jointly to William S. Boyle and George E. Smith for the invention of an imaging semiconductor circuit – the CCD sensor.
## A race between mm waveguide and optical communication

<table>
<thead>
<tr>
<th>Millimeter Waveguide</th>
<th>Optical Communication</th>
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<tbody>
<tr>
<td>Mature technology</td>
<td>Unknown technology</td>
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<tr>
<td>Ready for deployment</td>
<td>Promising but nothing is sure</td>
</tr>
<tr>
<td>Expensive</td>
<td>Potentially low cost</td>
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<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>
</tr>
</tbody>
</table>

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Courtesy from Nobel Lecture 2009
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

Courtesy from Nobel Lecture 2009
Milestones: World's First Low-Loss Optical Fiber for Telecommunications

The World's First Low-Loss Optical Fiber for Telecommunications, 1970

In 1970, Corning scientists Dr. Robert Maurer, Dr. Peter Schultz, and Dr. Donald Keck developed a highly pure optical glass that effectively transmitted light signals over long distances. This astounding medium, which is thinner than a human hair, revolutionized global communications. By 2011, the world depended upon the continuous transmission of voice, data, and video along more than 1.6 billion kilometers of optical fiber installed around the globe.

During the mid-1960s, members of the British Post Office came to Corning seeking assistance in creating pure glass fiber optics. Their design required a single-mode fiber (100 micron diameter with a 0.75 micron core) having a total attenuation of about 20 dB/km. The very best bulk optical glasses of the day had attenuations of approximately 3,000 dB/km. This meant Corning's scientists had to see an improvement in transparency of 1,096 in order to reach the 20 dB/km goal. It seemed impossible, but they did it, inventing an optical fiber with an attenuation of 17 dB/km. As a result, Corning's invention of the first low-loss optical fiber and the manufacturing process used to produce it revolutionized the telecommunications industry and changed the world forever. The explosion of the Internet and other information technologies would not have been possible without optical fiber. Only optical fiber provides the bandwidth required for high-speed transmission of voice, data, and video. The world depends upon for the way we live, work, and play. Today, there are more than 1.6 billion kilometers of fiber installed around the globe.

This breakthrough work established the optical fiber category. There were no similar achievements at the time of the invention. In recognition of this achievement, the three scientists responsible for inventing low-loss optical fiber—Dr. Robert Maurer, Dr. Peter Schultz, and Dr. Donald Keck—have been inducted into the Inventors Hall of Fame and were awarded the National Medal of Technology.
John Tyndall

From Wikipedia, the free encyclopedia

This article is about the scientist. For the British politician, see John Tyndall (politician). For the poet, see John Tyndall (Canadian poet).

John Tyndall FRSE (2 August 1820 – 4 December 1893) was a prominent 19th century physicist. His initial scientific fame arose in the 1850s from his study of diamagnetism. Later he made discoveries in the realms of infrared radiation and the physical properties of air. Tyndall also published more than a dozen science books which brought state-of-the-art 19th century experimental physics to a wide audience. From 1863 to 1887 he was professor of physics at the Royal Institution of Great Britain in London.

Contents

1 Early years and education
2 Early scientific work
3 Main scientific work
   3.1 Molecular physics of radiant heat
4 Alpine mountaineering and glaciology
5 Education
6 Dismantling of science from religion
7 Private life
8 John Tyndall's books
9 Biographies of John Tyndall
10 See also
11 Notes and references
12 External links

Early years and education

Tyndall was born in Leighlinbridge, County Carlow, Ireland. His father was a local police constable, descended from Gloucestershire emigrants who settled in southeast Ireland around 1670. Tyndall attended the local schools in County Carlow until his late teens, and was probably an assistant teacher near the end of his time there. Subjects learned at school notably included technical drawing and mathematics with some applications of those subjects to land surveying. He was hired as a draftsman by the government's land surveying & mapping agency in Ireland in his late teens in 1839, and moved to work for the same agency in England in 1842. In the decade of the 1840s, a railroad-building boom was in progress, and Tyndall's land surveying experience was valuable and in demand by the railway companies. Between 1844
John Tyndall Award

The John Tyndall Award is presented annually to a single individual who has made outstanding contributions in any area of optical-fiber technology, including optical fibers themselves, the optical components used in fiber systems, as well as transmission systems and networks using fibers. The contributions which the award recognizes should have met the test of time and should have been of proven benefit to science, technology, or society. The contributions may be experimental or theoretical.

First presented in 1987, this award is jointly sponsored by the IEEE Photonics Society and The Optical Society (OSA). The award is endowed by Corning, Inc., and consists of a specially commissioned crystal sculpture, a scroll, and an honorarium. The presentation is made the following year at the Optical Fiber Communication Conference (OFC).

Nomination Deadline: August 10. Obtain form and submit all nomination material to IEEE Photonics Society.

Winners

2015 - P. Daniel Dagkis
2014 - Kazuo Kikuchi
2013 - James J. Coleman
2012 - John E Bowers
2011 - David F. Welch
2010 - C. Randy Giles
2009 - Joe Charles Campbell
2008 - Robert Tkach
Development of Digital Telecommunications

Bit Rate

1850 1900 2000 1950
Year

Optical Fiber Communications 1970-2004, 30+ years

Telegraph
Radio
Submarine Cable
Advanced Fiber Optics
Fiber Optics

1960 Laser
1970 Low-Loss Optical Fiber

1960/70
Important Scientific Developments for Optical Communication

1958  Invention of first laser
1966  Light confinement in optical fiber predicted
       (Charles Kao); fiber loss at 1000dB/km
1970  Continuous wave room temperature operation of
       semiconductor laser; fiber loss at 20dB/km
1978  First light wave communication system deployed
       (wavelength at 800nm, 50-100Mbps, 10km repeater spacing)
1979  Fiber loss down to 0.2 dB/km
1987  First optical fiber amplifier at wavelength 1550nm
1990  In the nineties, Wavelength Division Multiplexing was
       developed and deployed extensively.
2001  Dense WDM now carries many more
       channels and all-optical network will be feasible.

...
Laser Invention
Operational Principle of Laser (Light Amplification by Stimulated Emission of Radiation)

(a) Before absorption

(b) After absorption

(a) Before stimulated emission

(b) After stimulated emission

Fiber Optic Communications, Fundamentals and Applications, S. Kumar & M. J. Deen, Wiley
"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle"
Nobel laureate and laser inventor Charles Townes dies at 99

By Robert Sanders, Media Relations | January 27, 2015
Optical Amplifier Invention
Optical Amplifier

- Optical – Electrical – Optical (OEO)

- All-Optical
Erbium Doped Fiber Amplifier (EDFA)

A three-level system

Level 3

Level 2

Ground level 1

Non-radiative transition

$\hbar \omega_p$

$\hbar \omega_s$

・摻铒光纖放大器

Fiber Optic Communications, Fundamentals and Applications, S. Kumar & M. J. Deen, Wiley
The Millennium Prize Laureates 2008

"For their outstanding contributions to telecommunications through the invention and development of the erbium-doped fibre amplifier (EDFA) which enabled the global high-capacity optical fibre network."

Professor Emmanuel Desurvire
Director of the Physics Research Group at Thales Research & Technology, France

Dr. Randy Giles
Director of Optical Subsystems and Advanced Photonics at Alcatel-Lucent Bell Labs, USA

Professor David Payne
Director, Optoelectronics Research Centre, University of Southampton, UK
Wavelength Division Multiplexing (WDM)
Wavelength Division Multiplexing (WDM)
BOULDER, Colo., Jan. 4, 2013 — Tingye Li, renowned for his contributions to lightwave technology and optical fiber communications, died Dec. 27, 2012. He was 81.

Born on July 7, 1931 in Nanjing, China, Li moved to Canada at age 12, and later to the US. He earned his bachelor’s degree from the University of Witwatersrand in South Africa and his doctorate from Northwestern University. He joined Bell Telephone Laboratories (later AT&T Bell Laboratories) in 1957, and worked there until his retirement in 1998.

During his 41-year career at AT&T, Li collaborated in developing crucial early understanding of laser cavities and made pioneering contributions to laser-based communication through optical fibers. In 1961, he and research partner A. Gardner Fox used computer simulation techniques to show that an open-sided resonator containing a laser medium should have unique modes of propagation, a fundamental principle in the theory and application of lasers.

In the late 1980s, when the world’s attention on optical communication was still focused on a single-channel high-speed solution, Li and colleagues developed the first (sparse channel) wavelength-division multiplexing (WDM) system. Their experiment in 1992 at Roaring Creek turned out to be a “roaring success” as Li said in an interview, allowing 2.5-Gb/s transmission per channel, the highest rate available at the time. The use of WDM and optical amplifiers changed the paradigm of network economics and is considered to be of revolutionary significance in the history of lightwave communications.

Li was active in SPIE and a member of OSA since 1966. He was named an OSA Fellow in 1977, served as an At-Large Member of its board of directors from 1985-1987, and as its president in 1995. He chaired numerous OSA committees, and was a leader in building the OSA-co-sponsored Asia Communications and
Wavelength Division Multiplexing (WDM)

- Channels transmitted by different optical carriers
- Allow multiple wavelengths transmitted over a single fiber

wavelength separation:
- WDM : > 1 nm
- DWDM : ~ 0.8 nm (100GHz)
- UDWDM: ~ 0.4 nm (50GHz)

- n-channel point-to-point WDM system

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multiplexer

optical fiber

amplifiers

demultiplexer