OPTI510R: Photonics

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Optical Amplifiers

- Erbium Doped Fiber Amplifiers (EDFAs)
- Semiconductor Optical Amplifiers
- Raman Amplifiers
- Optical Parametric Amplifiers
Four-wave-mixing

\[ \mathbf{P} = \varepsilon_0 \left( \chi^{(1)} \cdot \mathbf{E} + \chi^{(2)} : \mathbf{E}\mathbf{E} + \chi^{(3)} : \mathbf{E}\mathbf{E}\mathbf{E} + \cdots \right) \]  
(Induced polarization)

\[ \mathbf{P}_{\text{NL}} = \varepsilon_0 \chi^{(3)} : \mathbf{E}\mathbf{E}\mathbf{E}, \]  
(third order nonlinear polarization term)

Consider four optical waves oscillating at frequencies \( \omega_1, \omega_2, \omega_3, \) and \( \omega_4 \) and linearly polarized along the same axis \( x \). The total electric field can be written as:

\[ \mathbf{E} = \frac{1}{2} \mathbf{x} \sum_{j=1}^{4} E_j \exp[i(k_jz - \omega_jt)] + \text{c.c.}, \]

\[ \mathbf{P}_{\text{NL}} = \frac{1}{2} \mathbf{x} \sum_{j=1}^{4} P_j \exp[i(k_jz - \omega_jt)] + \text{c.c.}, \]
Four-wave-mixing

We find that $P_j \ (j = 1 \text{ to } 4)$ consists of a large number of terms involving the products of three electric fields.

For example, $P_4$ can be expressed as:

$$P_4 = \frac{3\varepsilon_0}{4} \chi^{(3)}_{xxxx} \left[ |E_4|^2 E_4 + 2(|E_1|^2 + |E_2|^2 + |E_3|^2)E_4 ight.$$ 
$$+ 2E_1 E_2 E_3 \exp(i\theta_+) + 2E_1 E_2 E_3^* \exp(i\theta_-) + \cdots \right],$$

where $\theta_+$ and $\theta_-$ are defined as

$$\theta_+ = (k_1 + k_2 + k_3 - k_4)z - (\omega_1 + \omega_2 + \omega_3 - \omega_4)t,$$
$$\theta_- = (k_1 + k_2 - k_3 - k_4)z - (\omega_1 + \omega_2 - \omega_3 - \omega_4)t.$$
Four-wave-mixing

There are two types of FWM. The term containing $\theta_+$ corresponds to the case in which three photons transfer their energy to a single photon at the frequency $\omega_4 = \omega_1 + \omega_2 + \omega_3$. This term is responsible for the phenomena such as third-harmonic generation ($\omega_1 = \omega_2 = \omega_3$). In general, it is difficult to satisfy the phase-matching condition for such processes to occur in optical fibers with high efficiencies.

The term containing $\theta_-$ corresponds to the case in which two photons at frequencies $\omega_1$ and $\omega_2$ are annihilated with simultaneous creation of two photons at frequencies $\omega_3$ and $\omega_4$ such that:

$$\omega_3 + \omega_4 = \omega_1 + \omega_2$$

The phase-matching requirement for this process to occur is:

$$\Delta k = k_3 + k_4 - k_1 - k_2 = (n_3 \omega_3 + n_4 \omega_4 - n_1 \omega_1 - n_2 \omega_2)/c = 0.$$
Four-wave-mixing

FWM efficiency governed by phase mismatch:

$$\Delta = \beta(\omega_3) + \beta(\omega_4) - \beta(\omega_1) - \beta(\omega_2)$$

In the degenerate case ($\omega_1 = \omega_2$), $\omega_3 = \omega_1 + \Omega$, and $\omega_4 = \omega_1 - \Omega$

Expanding $\beta$ in a Taylor series, $\Delta = \beta_2 \Omega^2$

FWM becomes important for WDM systems designed with low dispersion fibers!
Four-wave-mixing

PM PCF(20cm)

90/10
PM OC

Fiber-OPO

PM PCF(20cm)

Ring resonator

Cascaded FWM

Pump in

Output

Pump
FWM-good or bad?

- FWM leads to inter-channel crosstalk in WDM systems
- It can be avoided through dispersion management

On the other hand…

FWM can be used beneficially for:

- Parametric amplification and lasing
- Optical phase conjugation
- Wavelength conversion of WDM channels
- Supercontinuum generation
Summary

Major Nonlinear Effects:

- Self-Phase Modulation (SPM)
- Cross-Phase Modulation (XPM)
- Four-Wave Mixing (FWM)
- Stimulated Raman Scattering (SRS)
- Stimulated Brillouin Scattering (SBS)

Origin of Nonlinear Effects in Optical Fibers:

- Ultrafast third-order susceptibility $\chi_3$
M. E. Marhic, *Fiber Optical Parametric Amplifiers, Oscillators and Related Devices* (Cambridge University, 2007)


Optical Amplifiers

- Erbium Doped Fiber Amplifiers (EDFAs)
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- Raman Amplifiers
- Optical Parametric Amplifiers
An optical amplifier is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal.
Optical amplifiers are very important in modern communication system.
(a) Lightwave system with regenerative repeaters: Gain is provided by the electronics and each regenerative repeater is matched to the data rate of the system. (b) Lightwave system with erbium-doped fiber amplifiers (EDFAs): The amplifiers boost the signal independent of the data rate and allow multiple wavelengths.
Optical Amplifiers

Bit-Rate Distance Product

WHAT'S NEXT ??

- Spectrally-Efficient Modulation Formats
- WDM + Optical Amplifiers
- Optical Amplifiers
- Coherent Detection
- 1.5μm Single-Frequency Laser
- 1.3μm SM Fiber
- 0.8μm MM Fiber

Bit Rate-Distance (Gb/s • km)

Year

Types of Optical Amplifiers

Erbium Doped Fiber Amplifiers (EDFA’s)
- Best performance
- Low cost, robust
- Wide spread use

Semiconductor Optical Amplifiers
- Small package
- Potential use for low-cost applications
- Potential use for optical switching

Raman Amplifiers
- Better noise performance compared to EDFA

Optical parametric amplifier
- High gain, broader bandwidth
Note: The working principle of Raman and Parametric amplifiers is different
Erbium-doped fiber amplifier

- Working at around 1550nm
- Wide operating bandwidth
- Amplification of multiple channels
- Diode pumping
- Low cost, robust

First demonstration
Prof. David Payne and team
Published the research paper in the year 1987
at the University of Southampton, UK
Erbium-doped fiber amplifier

Energy diagram of Er-doped silica fiber
Erbium-doped fiber amplifier

Main pump wavelengths: 980nm and 1480nm
Main optical characteristics

- Amplifier gain: \[ G = 10 \log \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) \]
- Gain non-uniformity
- Gain bandwidth
- ASE
- Gain saturation
- Noise figure: \[ NF = \frac{(S/N)_{\text{in}}}{(S/N)_{\text{out}}} \]
Gain equalization
Gain bandwidth

Absorption and emission cross section

Gain as the function of wavelength
Amplified spontaneous emission

EDFA output spectrum measured by an optical spectrum analyzer.
Gain saturation

(a) Signal Output Power (dBm)
(b) Gain (dB)
(c) ASE Power (dBm)
(d) Total Output Power (dBm)

Need to operate at saturation!
\[ NF = \frac{(S / N)_\text{in}}{(S / N)_\text{out}} \]

\[ NF \text{ can be expressed as}:^* \quad NF = 10 \log \left( \frac{P_{\text{ASE}}}{h \nu \Delta \nu G} + \frac{1}{G} \right). \]

- \( P_{\text{ASE}} \) is the ASE power within the signal (filter) bandwidth \( \Delta \nu \).
- \( G \) is the amplifier gain.

Typical amplifier performance

Typical performance:
- High gain (30 - 50 dB)
- Low noise figure (3 - 6 dB)
- High output power (10 - 20 dBm)
- Flat gain (3 dB in 20 nm)
- High efficiency (40 - 80 %)
- Polarization insensitive

\[ \lambda_c = 1550 \text{ nm}, \; L = 10 \text{ m}, \; P_s = -20 \text{ dBm}, \; P_p = 50 \text{ mW} \]
Numerical modeling

Rate equations for a basic 3-level laser system

Let's introduce a basic three level laser system with energy levels shown below. The level 2 is the interesting metastable level, level 1 is the ground level and level 3 is the pump level. The rate equations corresponding to the fractional populations densities can be written as \((N_1 + N_2 + N_3 = N_{\text{total}})\):

\[
\begin{align*}
\frac{dN_1}{dt} &= -R_{13}N_1 + R_{31}N_3 - W_{12}N_1 + W_{21}N_2 + A_{21}N_2, \\
\frac{dN_2}{dt} &= W_{12}N_1 - W_{21}N_2 - A_{21}N_2 + A_{32}N_3, \\
\frac{dN_3}{dt} &= R_{13}N_1 - R_{31}N_3 - A_{32}N_3.
\end{align*}
\]

The symbols \(R_{13}, W_{21},\) and \(A\) correspond to pumping rates, stimulated emission rates and spontaneous decay rates; superscripts \(R\) and \(NR\) refer to radiative and non-radiative transitions, respectively. The symbol \(R_{31}\) refers to stimulated emission and the symbol \(W_{12}\) refers to stimulated absorption.
EDFA: Disadvantages

- Can only work at a narrow wavelength range (C and L band)
- Requires specially doped fiber as gain medium
- Three-level system, so gain medium is opaque at signal wavelengths until pumped
- Requires long path length of gain medium (tens of meters in glass)
- Gain very wavelength-dependent and must be flattened
- Gain limited by cooperative quenching
- Relatively high noise figure due to ASE
Semiconductor optical amplifiers

- Small package
- Potential use for low-cost applications
- Potential use for optical switching
Semiconductor optical amplifiers

Performance of a typical SOA

Compared to EDFA: Lower gain, high noise figure, and lower output power
Semiconductor optical amplifiers

Historically, SOA problems:

- SOA fast ($\sim 1\text{ ns}$) $\Rightarrow$ bit-timescale signal distortions

![NRZ signal](image1)

NRZ signal

![NRZ signal through SOA](image2)

NRZ signal through SOA

- Nonlinearities, four-wave mixing $\Rightarrow$ problem with WDM

$\Rightarrow$ EDFA preferred, except:

- Niche: transmissions outside C-band
- Niche: integrated amplifiers (e.g. with photodiode)
- Active MZI gates
- Signal processing: $\lambda$ conversion, regeneration...
Raman Fiber Amplifiers

Working principle of EDFA

Schematic of the quantum mechanical process taking place during Raman scattering

Raman Fiber Amplifiers

Raman gain profiles for a 1510-nm pump in three different fiber types. SMF, standard single mode fiber; DSF, dispersion shifted fiber; DCF, dispersion compensating fiber.
Raman Fiber Amplifiers

Schematic diagram of a Raman amplifier
Raman Fiber Amplifiers

Evolution of signal power in a bidirectionally pumped, 100-km-long Raman amplifier as the contribution of forward pumping is varied from 0 to 100%

Which one is better? Co-pumping or Counter-pumping?
Raman Fiber Amplifiers

Pros:

• Works at any wavelength (just need appropriate pump wavelength)
• Distributed amplification (better NF)
• Broad gain bandwidth (with the use of multiple pump wavelengths)
• Dual pumping (gain over whole transmission span)

Cons:

• Non-uniform gain (need multiple pump lasers)
• Pump noise transfer (Raman process is very fast)
• Multi-path interference
Raman Fiber Amplifiers

Schematic diagram of the discrete Raman amplifier comprising five wavelength WDM pumping and DCF as the gain fiber.
Numerically simulated composite Raman gain (solid trace) of a Raman amplifier pumped with six lasers with different wavelengths and input powers.
Measured power spectrum from a 50-km-long Raman amplifier in which 40 signal channels propagate in the C band (counter pumping). The fiber type was a TrueWave fiber but in this case an on–off gain of 20 dB was achieved using a total pump power of 650 mW.
Optical Parametric Amplifier

Degenerate and non-degenerate FWM process depicted on an energy level diagram

Require optical fiber with zero dispersion near the pump wavelength for phase matching
Optical Parametric Amplifier

Parametric gains are on both side of the pump laser

$G=1/4 \exp(2 \gamma P_p L)$

$G=(\gamma P_p L)^2$
Optical Parametric Amplifier

FOPO with 70dB gain!
Optical Parametric Amplifier

Advantages:

• Gain bandwidth increasing with pump power
• Arbitrary center wavelength
• Very large gain (70dB)
• Unidirectional gain (no need for isolator)
• Compatibility with all-fiber devices
• High power capability
• Distributed amplification (low noise figure)
Questions for thoughts

- What is the amplifier of choice for the next generation of lightwave communication systems?

- Can you come up with a new type of optical amplifier that would work much better than the current ones?

- Can we have an amplifier without added noise?

- Can we modify the Erbium atoms to make them provide larger gain bandwidth?
M. E. Marhic, *Fiber Optical Parametric Amplifiers, Oscillators and Related Devices* (Cambridge University, 2007)
