Fiber lasers and amplifiers

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Outlines

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• Fiber laser research at the College of Optical Sciences
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Introduction

Nobel Prize in Physics awarded for contribution related to laser

- 1964: Townes, Basov and Prokhorov
- 1971: Gabor
- 1981: Bloembergen and Schawlow
- 1997: Chu, Cohen-Tannoudji and Phillips
- 2000: Alferov and Kroemer
- 2005: Hänsch an Hall
Laser market

2013

- Communications: 31%
- Materials processing: 25%
- Optical storage: 14%
- Lithography: 8%
- R&D & military: 7%
- Medical & aesthetic: 6%
- Sensors: 5%
- Displays: 2%
- Printing: 1%
Laser market

![Pie chart showing market share by technology: Diode 58%, CO2 16%, LPSSL 9%, DPSSL 6%, Excimer 6%, Fiber 4%, Other 1%]
History

First laser was demonstrated in 1960 by T. Maiman

First fiber laser was demonstrated in 1963 E. Snitzer

Amplification in a Fiber Laser

Charles J. Koester and Elias Snitzer

Fiber lasers of neodymium-doped glass have been
To prevent oscillation, the ends are polished at an
With the high inversion which can then be obtained
1-m long fiber. The gain was measured as a function
the pumping pulse at which the amplification was

Fig. 1. Coiled fiber laser. From the top the components are:
cavity, fiber laser, flash tube, and 18 cm scale
Who invented the laser?

Concept for the MASER, May 11, 1951

Charles Townes & Jim Gordon

Figure 9. James Gordon (at right) and I were photographed with the second maser at Columbia University. The normally evacuated metal box where maser action occurred is opened up to show the four rods (quadrupole focusor) which sent excited molecules into a resonant cavity (the small cylinder to the right of the four rods). The microwaves that were generated emerged through the vertical copper waveguide near my hand. This second maser was essentially a duplicate of the first operating one, and it was built to examine the purity of maser signals, by allowing the two to beat together, thus producing
Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation.

Consider a tube terminated by optically flat partially reflecting parallel mirrors. The mirrors might be silvered or multilayer interference reflectors. The latter are less loss and may have an arbitrarily high reflectance depending on the number of layers. An important achievement is 98% in the visible for a 7-layer reflector. Float with less than 1/1000 λ are not available, so, if a resonant system is desired, higher reflectance would not be useful. However, for a nonresonant system, the 99.9% reflectors which are possible might be useful.

Consider a plane wave in the tube. This is the effect of a closed cavity since the vacuum wavelength is small. The diffraction and hence the lateral loss is negligible.

Who invented the laser?
Who invented the laser?

- Charles Hard Townes and Arthur Leonard Schawlow
- Gordon Gould
- N. Basov and A. Prokhorov
- Nico Blombergen
How does a laser work?

Lasers tend to operate in a mode so that the optical field in the cavity sees smallest loss per cavity round trip.
How does a laser work?

We need to have 3 things put together in a certain way to make a laser:

1. Pump to create a population inversion
2. Gain medium where the population inversion occurs
3. Cavity to provide a positive feedback for the field to build up
Is this really a laser?

High-Gain Backward Lasing in Air

Arthur Dogariu,1,4 James B. Michael,1 Marlan O. Scully,1,2 Richard B. Miles1

The compelling need for standoff detection of hazardous gases and vapor indicators of explosives has motivated the development of a remotely pumped, high-gain air laser that produces lasing in the backward direction and can sample the air as the beam returns. We demonstrate that high gain can be achieved in the near-infrared region by pumping with a focused ultraviolet laser. The pumping mechanism is simultaneous resonant two-photon dissociation of molecular oxygen and resonant two-photon pumping of the atomic oxygen fragments. The high gain from the millimeter-length focal zone leads to equally strong lasing in the forward and backward directions. Further backward amplification is achieved with the use of earlier laser spark dissociation. Low-divergence backward air lasing provides possibilities for remote detection.

Optical techniques for the remote detection of atoms and molecules rely on the use of lasers to selectively identify and quantify species of interest. To enable single-sided detection, collection of light must be accomplished in the backward direction. Collection of incoherent light emission from molecules of interest is limited by the nondirectional nature of spontaneous emission. More sensitive detection techniques, aided by the coherent nature and well-defined direction of emission, are restricted in the direction of emission by the phase-matching relation. For commonly employed nonlinear techniques such as coherent anti-Stokes Raman spectroscopy (1) and stimulated Raman scattering (2), phase-matching results in a coherent beam propagating in the direction of the pumping laser, away from the source.

These limitations have motivated the exploration of backward air lasing and stimulated gain concepts, which can produce coherent scattering that returns to the pump-laser location (3). To date, the only approach that has shown promise is based on the electron recombination of ionized molecular nitrogen from a femtosecond-produced filament (4, 5). This scheme leads to gain at 337 nm, the same wavelength as the molecular nitrogen laser. Amplified spontaneous emission gain on two-photon excitation of one of the resulting oxygen atom fragments. Both processes are resonantly enhanced at the 226-nm wavelength of the pump laser. The excitation is followed by lasing from the excited atomic oxygen (Fig. 1A). The pump laser is focused such that there is no laser-induced breakdown of the air, and excitation followed by stimulated emission is achieved throughout the 1-mm-long focal region. The result is the formation of well-collimated backward and forward propagating laser beams at 845 nm with parameters corresponding to the ultraviolet (UV) pump-beam focusing.

Two-photon laser-induced fluorescence from atomic oxygen has been developed for qualitative diagnostics of combusting gases where atomic oxygen is an important radical species (6–10). The two-photon excitation transition is from the 2pP ground state to the 3pP excited state with 226-nm laser radiation. That excitation is followed by spontaneous relaxation from the 3pP state to the 3sS state, producing fluorescence emission at 845 nm (Fig. 1A). The use of the two-photon excitation to produce stimulated emission at 845 nm in atomic oxygen has been observed in flames at subatmospheric pressures (11).

The same two-photon transition can be used as the initial step in a 2+1 resonance enhanced multiphoton ionization (REMPI) (12). This process can be remotely monitored by microwave scattering from the free electrons [radar REMPI
Why are people still doing research in lasers?

The physics of laser operation is well understood. But there is always need for better and cheaper lasers. Also, there are still a lot of applications’ requirements that current technology cannot satisfy.

Requirements:

- New wavelength bands
- Maximum average output power
- Maximum peak output power
- Minimum output pulse duration
- Maximum power efficiency
- Minimum cost
Active fibers

- Nd³⁺, Yb³⁺
- Er³⁺
- Tm³⁺, Ho³⁺
- Bi³⁺
- Pr³⁺

Wavelengths:
- 491 nm, 520 nm, 605 nm, 695 nm

Diameter:
- 0.5 μm
- 1 μm
- 1.5 μm
- 2 μm
- 3 μm

ZBLAN
Advantages of fiber format

Fiber format removes the strict requirement of heat management which is normally very critical in solid-state lasers.

But there are also disadvantages:

- Long gain media
- High nonlinearity
- Polarization stability

- High efficiency
- Air-cooled
- Direct diode pumping
- Compact
- Alignment free
- Reliable
- Low cost
- Performance
Laser design
Fiber laser performance

Growth of Yb:HPFL SM
(near diffraction limited)

Power (W)

Year


3 10 20 35 50 100 500 1000 2000 3000 5000 10kW in 2010!
mJ energy femtosecond fiber laser: > 1GW peak power!
What can fiber laser do?

Overlay locus of high-power fiber lasers

- Polymer welding
- Brazing
- Hardening
- Cladding
- Welding, sintering
- Deep-penetration welding
- Non-metal cutting
- Metal cutting
- Printing technology
- Soldering
- Marking
- Drilling

Source: P. Loosen, Fraunhofer Inst., Fuer Lasertechnik, Aachen, Germany
Cladding pump technology

http://www.rp-photonics.com/double_clad_fibers.html
Cladding pump technology

Fig. 1. V-groove side-pumping arrangement.

(US patent # 5,864,644)

(Goldberg, Opt. Lett. 1999)

GTWave technology (credit: D. Payne)
Beam combination

Future Steerable 1 MW Design? Multi-path MOPA

Lengths matched to within coherence length of source

DFB fiber laser

Phase-coherent output for synthetic-aperture source

Single-mode
Single-frequency
Single-polarization

(credit: D. Payne)
Fiber laser research at the College of Optical Sciences

**Achievements – Phosphate Glass Fiber Lasers**

- **Materials & Fiber Development:**
  - low loss fiber (~ 0.01 dB/cm)
  - microstructured active fiber
  - photosensitive passive and active fiber

- **Phosphate glass fiber lasers:**
  - single-mode lasers generating > 1 W/cm
  - cladding pumping schemes for W-level single-frequency DBR and DFB lasers

Fiber Bragg Grating in phosphate glass fiber

Reflection > 92%
Fiber laser research at the College of Optical Sciences

Highly doped Yb-Er phosphate fiber
Fiber laser research at the College of Optical Sciences

Single-Frequency Microstructured Fiber Lasers

Dielectric Coating

3.8 cm active phosphate fiber

Bragg grating in silica fiber

Output Power (W)

Pump Power (W)

Fiber with PCF cladding (3.8 cm)
Step-index fiber (4 cm)
Cladding pump technology

Polynkin, 2004
Reflector with ultra-narrow bandwidth

Allow single-frequency operation even when the cavity is long.

Understanding the reflectivity of microsphere resonator

Microsphere resonator

Fabry-Perot resonator
Fiber amplifier

http://www.rp-photonics.com
Fiber amplifier
Fiber laser
Laser characteristics

- Directional emission
- Clear lasing threshold
- Spectral narrowing

Required components:
- Gain medium
- Pump
- Cavity
Femtosecond pulse generation with carbon nanotubes
Femtosecond pulse generation with carbon nanotubes

Femtosecond pulse generation with carbon nanotubes

Old technology

New technology
Future directions

- New fiber design with increased MFD to reduce nonlinear effects
- New doped fibers operating at other spectral regions
- Generation of new frequencies
- Pulsed source with ultra-high peak power
- Compact lasers for precision measurement and sensing

(Credit: Nufern.com)
Questions for thoughts

• Can fiber lasers be used for all applications?

(Think of a application that current fiber lasers can not be used)

• What is the power limit of fiber lasers?

• Is that important to know exactly who invented the laser?

• How many more years are we going to do research on laser?

• Can we use lasers to predict earthquakes?

If you don’t know what tool to use, take a laser!