Recent Advances in Photonic Devices for Optical Super Computing

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Introduction

- Computers have enhanced human life to a great extent.
- The speed of conventional computers is achieved via VLSI technology in miniaturizing electronic components to a very small micron-size scale.
- VLSI reached 0.08 µm (Lucent Technology).
- VLSI technology established the 20th century as the computer age.
- This millennium is strongly believed to be that of photonic materials and optical technology.

Electronics Limitations

- VLSI technology is approaching its fundamental limits in the sub-micron.
- VLSI technology can no longer keep up with Moor's Law. (transistors~5ps, but computer cycle time~5ns)
- Sub-micron scale leads to dielectric breakdown, hot carriers, and short-channel effect, which affect the device reliability.

Optical Systems

- Optical components are widely used, durable and reliable.
- Photonic device sales worldwide are in the $100's of billions.
- Phillips Group in London estimates that the U.S. data traffic increases at a rate of 300% annually.
- Future Communication Inc., London, used wavelength division multiplexing at a total rate of more than 1000 Tb/s.

- The optical networking sale passed $3.5 billion by 2007, according to In-Stat/MDR, a market research firm.
- Chiaro Networks, in Dallas, Texas, with R&D office in Israel, demonstrated an Internet Protocol router capable of forwarding almost 8 billion packets per second. This is ~ 1,000 times the capacity of conventional packet switching.

- A European collaborative efforts demonstrated a high-speed optical data input and output in free-space between chips at a rate of more than 1 Tb/s.
- Astro Terra, in collaboration with Jet Propulsion Laboratory (Pasadena, CA) built a 32-channel 1-Ggb/s earth –to –satellite link with a 2000 km range.
- NEC (Tokyo, Japan) has developed a method for interconnecting circuit boards optically using VCSEL.
- Researchers at NTT (Tokyo, Japan) demonstrated 1000 interconnections per printed-circuit board, with throughput ranging from 1 to 10 Tb/s.

Optics Advantages:

- Optical materials possess superior storage density over magnetic materials.
- Optical devices have been incorporated into many computing systems.
- Optical components are immune to electromagnetic interference, and free from electrical short circuits.
- They have low-loss transmission and provide large bandwidth.
- They are capable of sending signals within the same or adjacent fibers with essentially no interference or cross-talk.

- Optical data processing can be done much easier and less expensive in parallel (Cray Computer).
- To appreciate optical parallelism, one can think of an imaging system of as many as 1000x1000 independent points per mm2 in the object plane which are connected optically by a lens to a corresponding 1000x 1000 points per mm2 in the image plane. For this to be accomplished electrically, a million nonintersecting and properly isolated wires per mm2 would be required.
- Parallelism, therefore, when associated with fast switching speeds, would result in staggering computational speeds.
- Assume, for example, there are only 10 million gates on a chip. Further, conservatively assume that each gate operates with a switching time of only 0.1 nanosecond.

- The data throughput is the product of the number of gates and their switching speeds. Such a system could perform more than 10^17 bit operations per second. Compare this to the gigabits (10^9) per second rates which electronics are currently limited to.
- Photons are uncharged and do not interact with one another as electrons. Consequently, light beams may pass through one another without distorting the information.

Optical computing as we envision will be:

1. More efficient,
2. More cost effective,
3. Lighter,
4. More compact,
5. Less cross-talk,
6. No short circuits,
7. Parallelism,
8. Orders of magnitudes higher in computing speed.

Limitations:

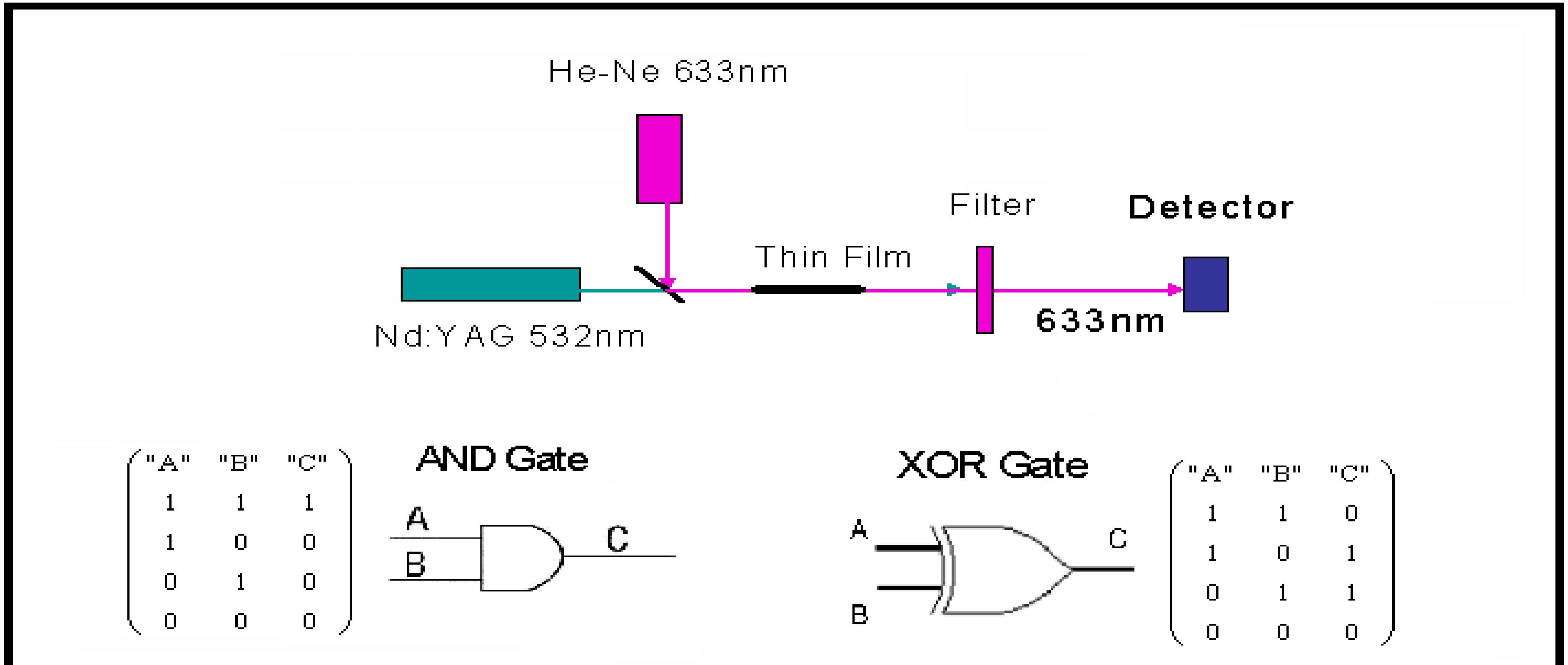
1. Cascading and Integration,
2. Size of optical circuits,
3. Nonlinear processes,
4. Laser size and power.

An overview of the current status of optical components for computing

- All-Optical Logic gates.
- Optical processors.
- Optical Storage
- Holographic storage.
- Optical interconnects.
- Spatial Light Modulators.
- Optical Materials

All-Optical Logic Gates

1. All Optical AND &XOR gates



Nanosecond All-Optical AND-Gate in Phthalocyanine film

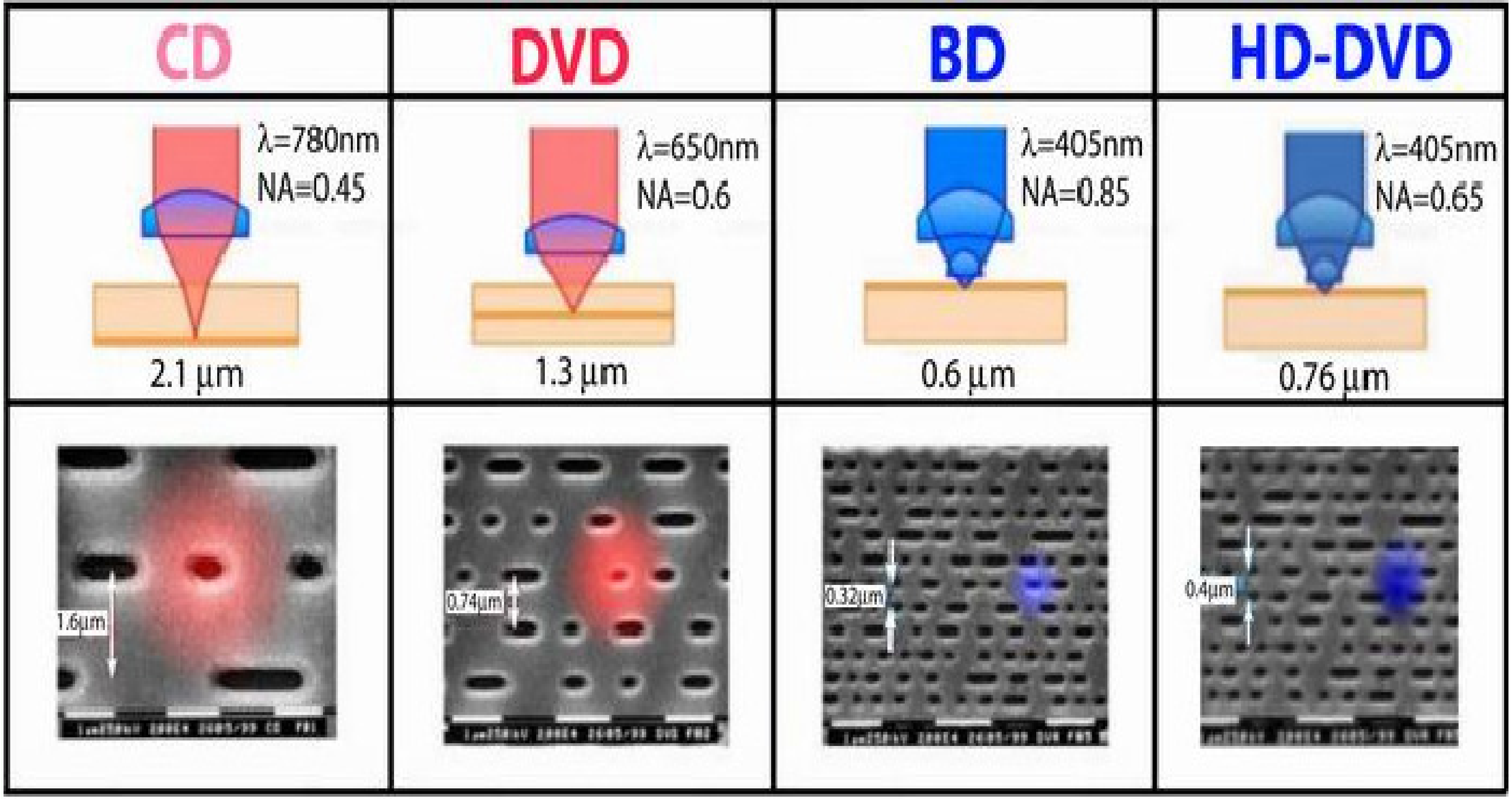
Picosecond All-Optical XOR Gate in Polydiacytelene film

- Li *et. al*. proposed an all-optical logic gate of SiGe/Si material with multifunctional performance that can function as OR, NOT, NAND, and NOR gates simultaneously or individually.
- An impressive 40 Gbit/s NOR all-optical logic gate has been demonstrated by Zang *et. al.* using a semiconductor optical amplifier (SOA) and an optical band pass filter.
- An even more impressive 80 Gbit/s NOR all-optical logic gate has been demonstrated by Liang *et. al.*.

2. Optical processors.

- Manipulate input information to produce meaningful outputs.
- On Jul 25, 2007 Intel claimed an optical processor breakthrough of 40Gbps.
- Lenslet has developed a processor at 8 trillion operations per second, which is 1000 times faster than standard processors.
- Tian *et.al.* developed an organic material as a fast optical processor for pattern –recognition in a sub-picosecond range. The size of the phase-encoding spectral interval exceeds 1 THz.

3. Optical Storage



Schematic of the different optical storage disks, the wavelength, the numerical aperture, and spot size for each, Munro.et.al.

- Optical storage is the natural alternative for magnetic recording systems. It has much more storage capacity and more reliability.
- Hitachi Maxell disc, which is only 1 cm longer in diameter than a CD can store up to 300 GB. Currently, a HD-DVD offers a maximum of 30 GB on a 2-layer disc, and Blu-ray Disc (BD) offers up to 50 GB.
- The future predictions expect to increase the storage density up to 800GB in two years, and up to 1.6TB by the year 2010.

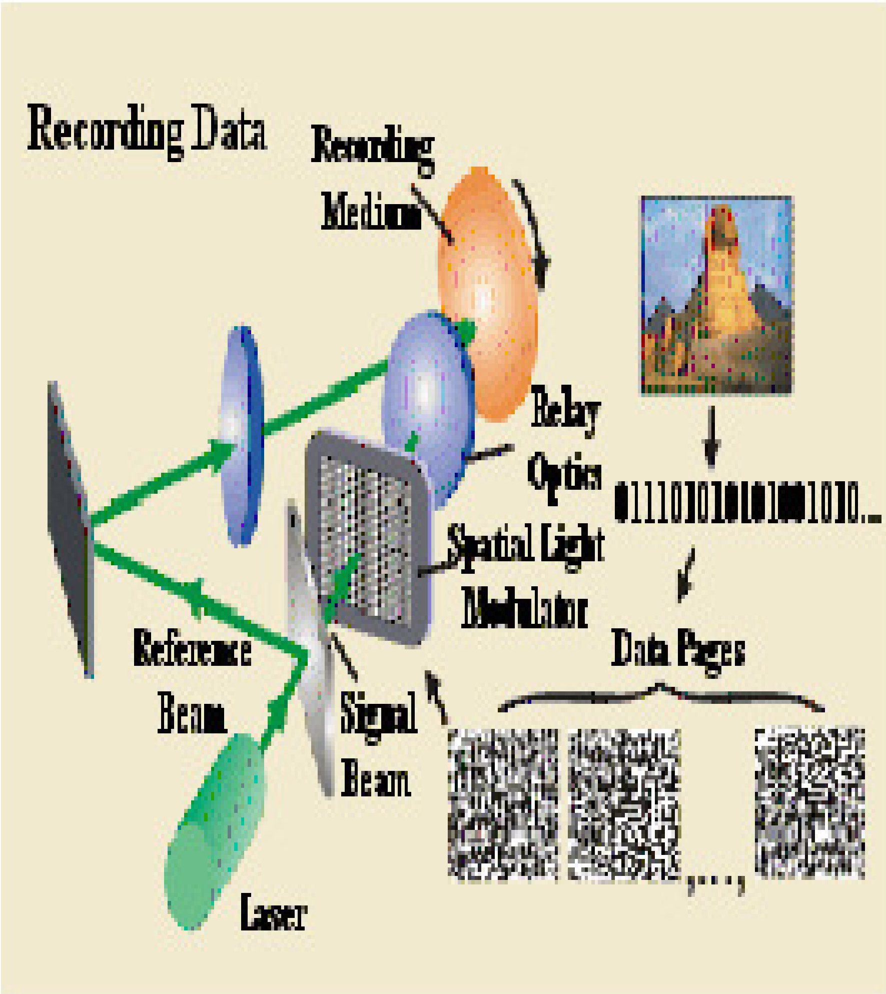
- Aprilis Inc. demonstrated an organic-inorganic composite with a storage capacity of 250 GB on a DVD-like disc with transfer rates exceeding 10 Gbps.
- Physicists at Imperial College London in collaboration with other institutions developed a CD with a storage capacity of 1TB. It is expected to be released between 2010 and 2015.

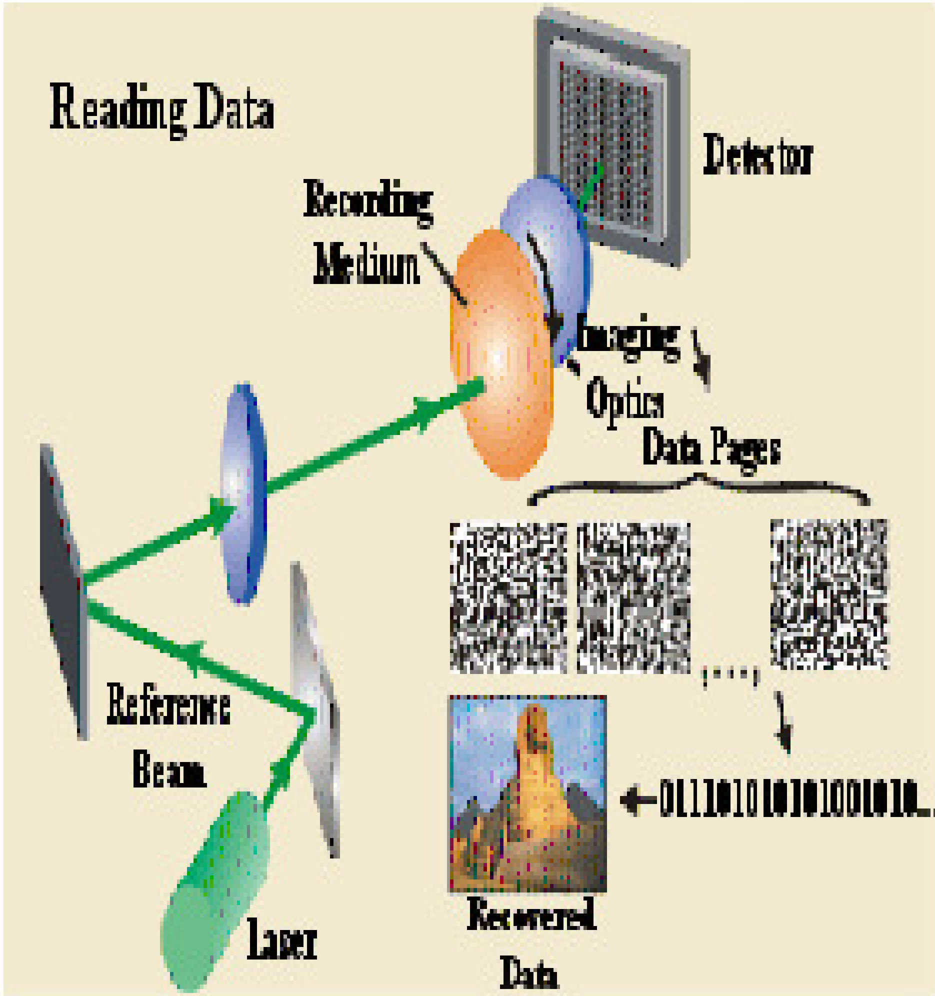
4. Holographic Storage

- The surface-storage techniques are approaching their fundamental limits. As the bits become smaller they become thermally unstable, difficult to access, and unreliable.
- Holography breaks the density limitations imposed by conventional surface storage techniques.
- The fundamental storage capacity is limited to ~ $V/\lambda 3$

- The hologram encodes a large block of data as a single entity in a single write operation and the information is retrieved back as a data block simultaneously.
- Holograms are used as tools in large scale ANN for voice and image recognition systems, robotics, medical imaging, data mining, and aerospace applications.

The hologram is constructed and read as shown (Lucent Technology)



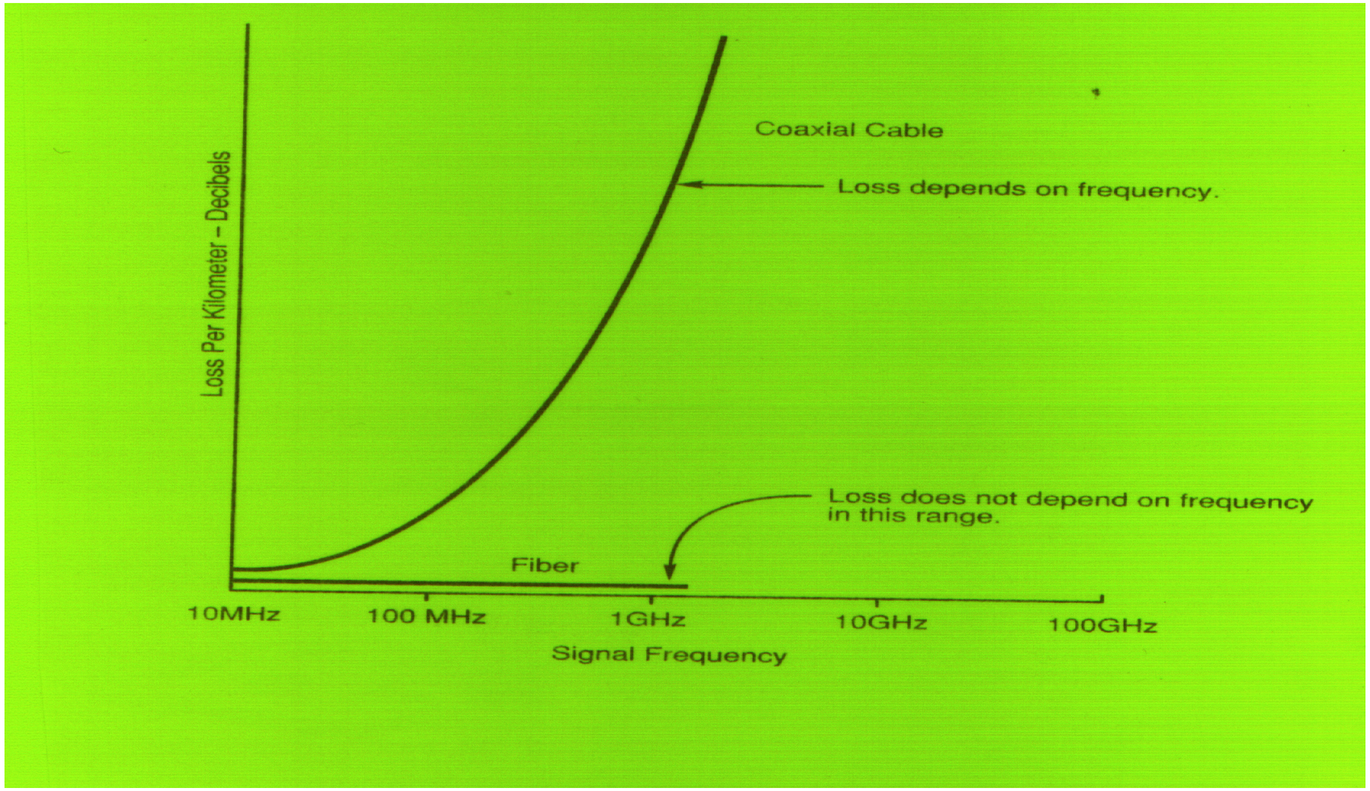


- Holograms are durable, compact, inexpensive, and reliable, which make them the future means of storing large size information and data processing.
- Wan *et al.* succeeded in storing 5000 images; each contains 768x768 pixels on a disk-made of 0.03wt% Fe doped LiNbO crystal.

- Researchers at IBM succeeded in storing 10,000 pages, one megabit each (10 gigabits), in a one centimeter cube recording material.
- Maxell USA and InPhase Technologies have now made available, on the market, holographic discs with 1.6 TB per disk and with data rates as high as 120MB/s and with 50+ year media archival life.
- M. Thomas the president of Colossal Storage Corporation demonstrated a holographic storage capacity on a 3.5-inch disc on the order of ~1.2 petabytes (10^18 bytes). The production of these disks for marketing is expected to be no sooner than 2012.

5. Optical Interconnects

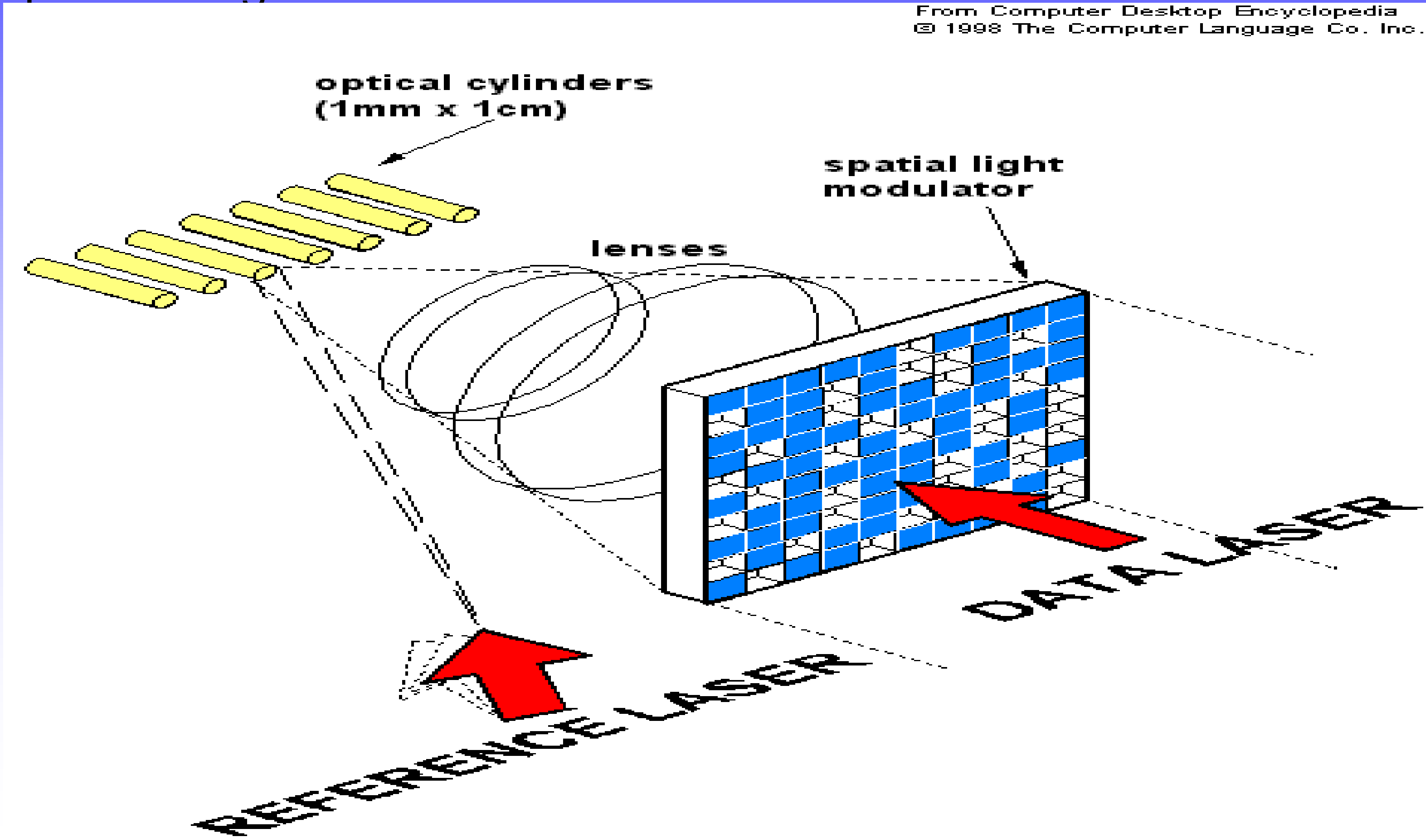
- Optical fibers became less costly and more widely used in links at local and wide area networks, as an alternative to electrical links.



- The backbone of the Internet uses fiber optics to transfer data over long distances.
- Optical fibers are immune to EMI, inexpensive, lighter, 0.4 dB/km at 1300nm and 0.25 dB/km at 1550nm. This allows carrying an optical signal to travel up to 100km without amplification (dozen amplifiers in coaxial cables).
- Multimode optical fibers allow links with a bit rate-distance product of more than 2 GHz.km (i.e., 4 Gb/s over 500 meters), while copper cables have a bit rate-distance product, which is ten times less.

6. Spatial Light Modulators (SLM)

- SLM are valuable components for neural networks and image processing.



- Common SLMs are made of micron-size pixels of Nematic liquid crystals, which have relatively slow modulation speed and a low contrast ratio.
- Recent advances have been developed using polymeric materials, which have high modulation speed and a high contrast ratio.
- Holoeye corporation developed high resolution SLMs of 1920x1200 pixels and pixel pitch of 8.1 μm.

7. Optical Materials and new photonic devices

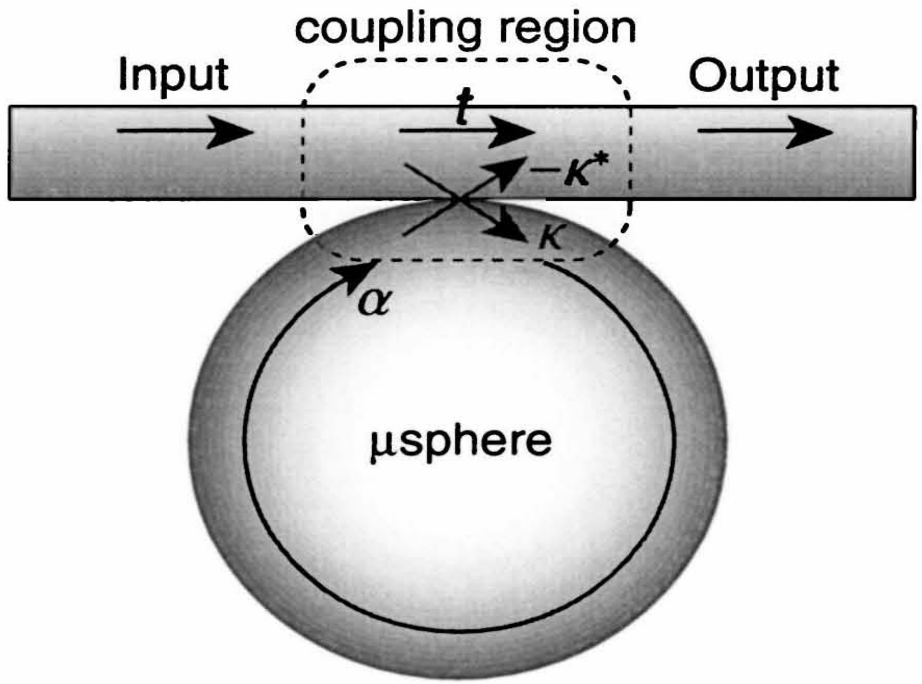
- Optical materials are crucial elements in the development of all-optical technology. The proper material to build an optical chip that can play the same role as semiconductor chip has not yet emerged. The different materials, which have been examined so far are:
- Photorefractive materials
- Semiconductors
- Doped micro-spheres
- Photonic Band Gap materials
- Organic and polymeric materials

- **Photorefractive (PR) materials**
- Photorefractive materials are those materials which their indexes of refractions are modified and altered by the presence of light ($BaTiO_3$, $LiTaO_3$, $LiNbO_3$).
- PR polymers are also of considerable interest for being less expensive, easy to manufacture, and are more flexible alternatives to the inorganic crystals.

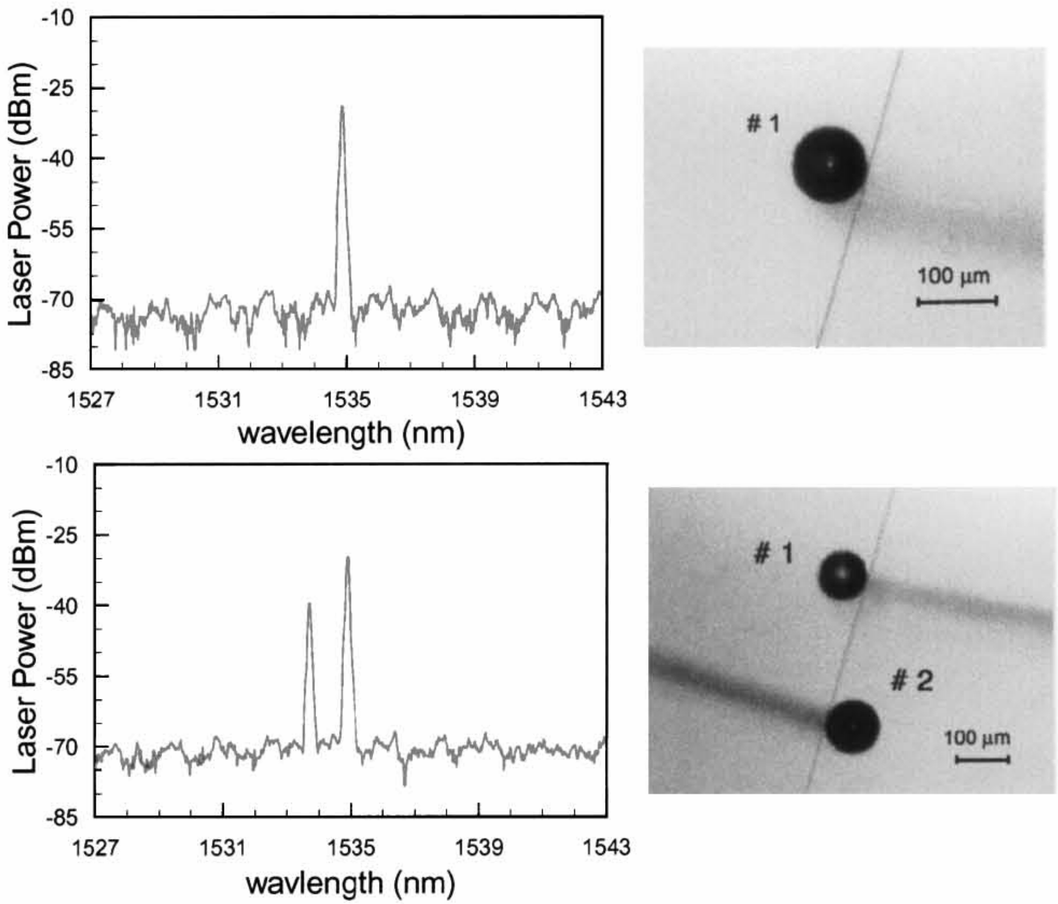
- **<u>Semiconductors</u>**
- Semiconductors are widely used to build lasers of different sizes at broad range of powers, and wavelengths for optical communication, remote sensing, optical data storage, and medical applications.
- Evident technologies came up with a new class of semiconductor nano-crystal quantum dots. They range in size from 2-10 nm. They are tunable between 490-2000 nm. They have shown switching speed in the 1-picosecond time frame.

Micro-spherical Laser

- It is important to note that all-optical logic gates on an optical chip are unlike electronic transistors on an electronic chip. The electronic transistors on a chip can all be activated by the same power supply, while all-optical logic gates are expected to perform using different light frequencies and intensities.

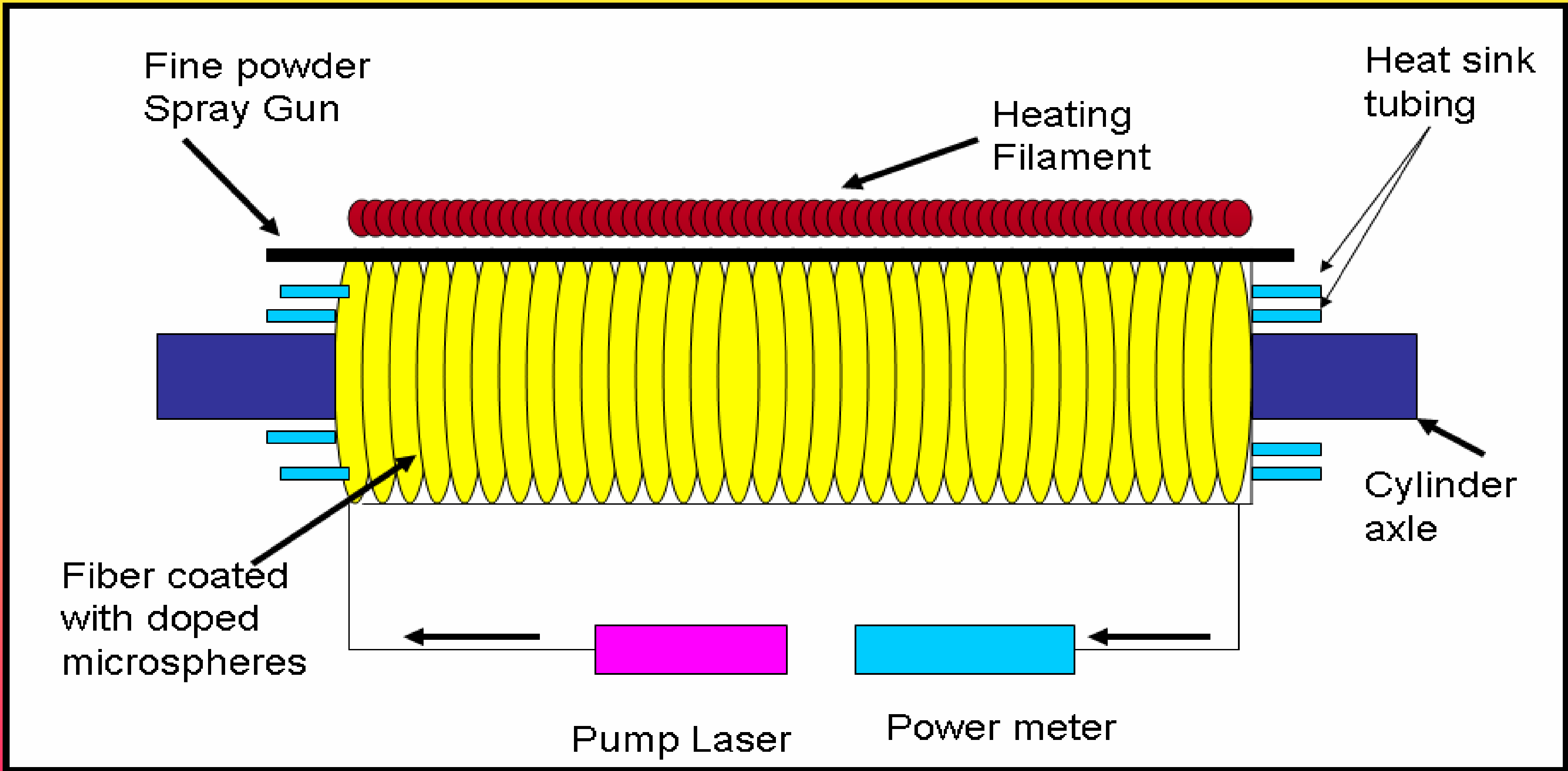


Schematic of the laser coupling from the input pump at one end of the fiber to the spheres and back to the fiber.

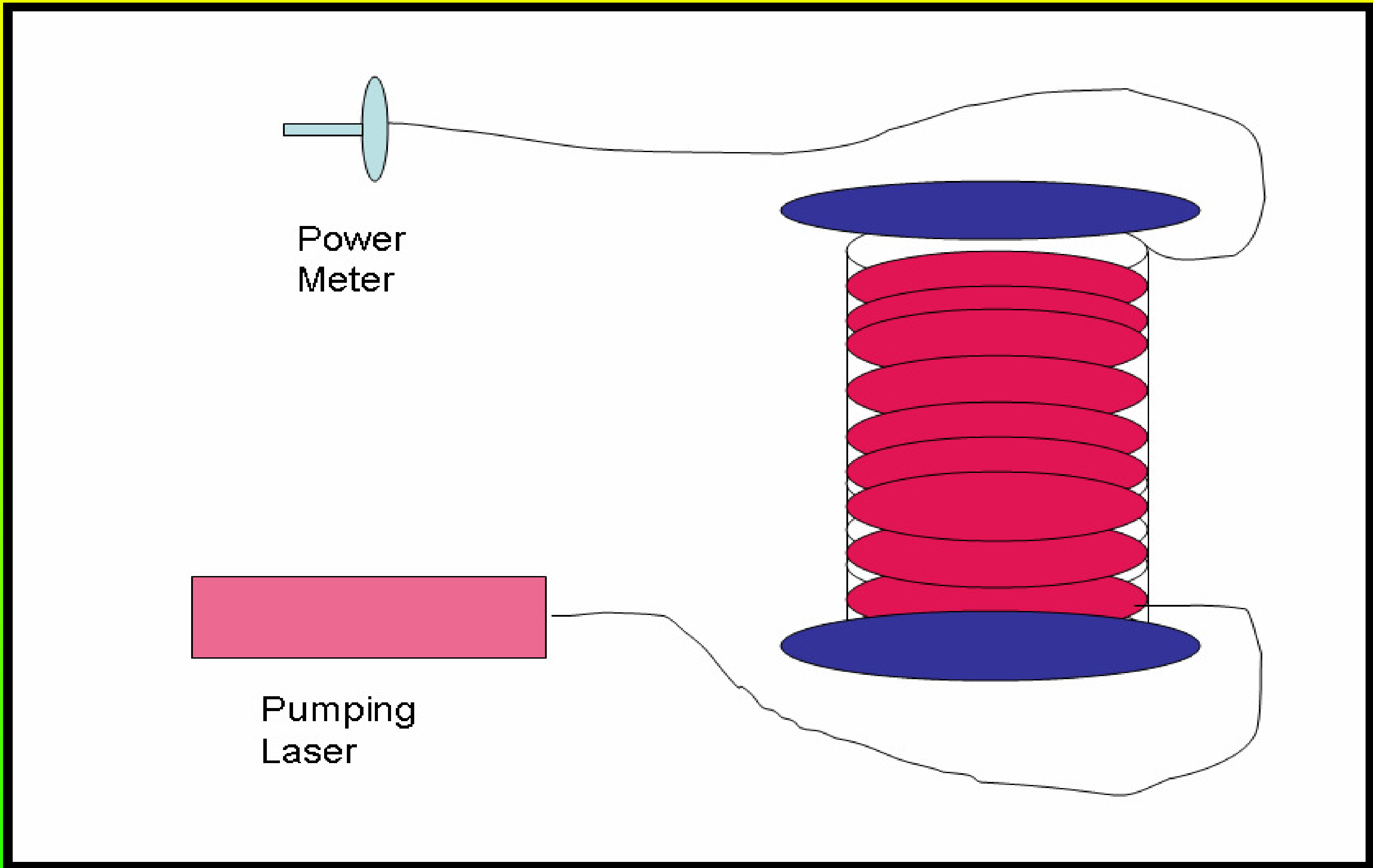


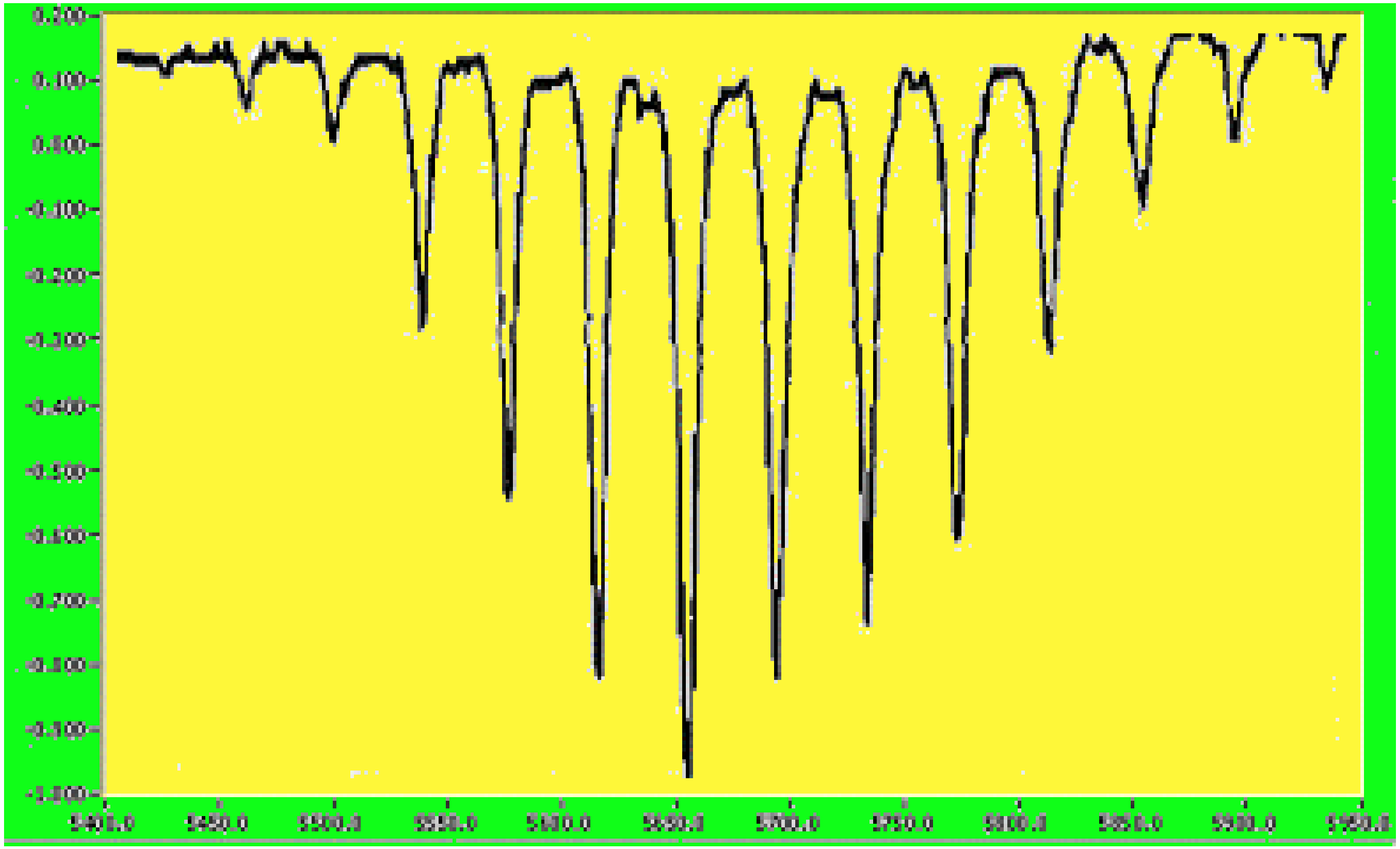
The top and bottom show a single and bi-spheres doped with erbium-ytterbium, tapered to a fiber and the spectral lines from each setup. The pump at 980-nm and the output from one sphere is at 1535 nm and from two different sizes spheres at 1533 and 1535 nm with a lasing threshold of 60 μW.

- Schematic of the process of attaching the microspheres to the fiber.



Schematic of the microspherical-fiber laser system.





The spectrum of 12 microns size silica spheres doped with Rhodamine-6G and pumped with 532nm.

Organic Compounds

- Organic materials have been demonstrated, as photorefractive, optical storage, electro-optical, and even magnetic materials.
- They are of use for Organic Light Emitting Diodes (OLED) for display technology, roll-up screens, head wearable displays, and other flexible electronic applications.
- OLED are now replacing LCDs found in cameras and mobile phones.
- OLED devices demonstrated four times higher efficiency and good mechanical properties (flexibility and toughness).

Photonic Band Gap Materials (PBG)

- Photonic Band Gap materials are similar to semiconductors, except the electrons are replaced by photons.
- PBG materials can act as a perfect mirror.
- PBG materials can be used to control and manipulate the spatial and temporal properties of light.
- Photonic crystals promise to give us control over photons similar to the control over the flow of electrons in a semiconductor.

- PBG materials are expected to play the role for optics as semiconductors for electronics.
- PBG hold potential for optical communications,and optical computing.
- The Department of Energy's Sandia National Laboratory are claiming that they have possibly solved the major technical problem of bending light easily and cheaply without leaking regardless of how many twists or turns are needed for optical communications or optical computing. If this is true, effective use of PBG materials will be a major step forward toward the building of an optical chip, and opens a window to the engineering of dielectric microstructures to make the photons flow in a way similar to electrical currents in semiconductor chips

- **Conclusion**
- We briefly presented some of the recent work and components of potential for the manufacturing of an optical computing system.
- The state of the art components demonstrate impressive high speed components with very high storage density and reliability, which bring optical computing closer to reality than ever before.
- why aren't optical computing systems yet in existence?

1. Optical technology relies, for the most part, on materials yet to be synthesized or developed. PBG crystals, are quite promising, and could become the "flesh and bones" of an optical chip. They can guide, rout, control and manipulate light, build laser diodes, optical transistors, confining or even slowing down light. More importantly, PBG materials have the potential for integrating many components into a single optical chip. Additionally, they promise extremely fast processing speeds, and can be activated by very low power.

2. Electronic transistors on a chip function by the same power supply, while optical components in order to perform, may require different light frequencies and intensities from different laser sources.
3. The issues of miniaturizing optical components, cascading, integrating and processing on a single chip are difficult problems yet to be solved.
4. Optical technology is multidisciplinary and relies on close cooperation between material scientists, physicists, organic chemists, computer architects, computer engineers, computer scientists, and mathematicians. There is a strong need for the government´s involvement to integrate and generously fund such inter-disciplined groups.
5. There is still the tendency among scientists and engineers to mimic conventional electronic systems in designing an optical computing system. This might not be the optimum way of thinking. There is a need for a paradigm shift in thoughts since electrons and photons are quite different in nature and the means of manipulating them are totally different.

Thank you