Optical Amplification

A Key to the Information Age

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October 29 marks the 50th anniversary of the first connection of two distant computers, widely recognized as the initial step in the development of the internet. That link between UCLA and Stanford validated a network control protocol for sending packets of data over arbitrary routes, a radical step in the days of point-to-point copper telephone and telegraph lines.

Today the transport network for delivering the world's data is 2 billion kilometers of optical fiber intertwining the globe. This super-structure has been variously referred to as the backbone, the core, the trunk or optical fiber links.[1] But all these pseudonyms are misnomers because they obscure the real magic of data transmission: most of our information in The Information Age travels on waves of light, on trillions of photons. Without these shining miniature suns, the Internet would be as black as the void of deep space.

Instead, light animates the Information Age to such an extent that in a sense, we live our lives on lightwaves, the power that carries virtually all of our texts, photos, texts, posts, videos and IP traffic that we and our machines generate. This phenomenon is enabled by two core inventions -- optical fiber and the optical amplifier. Let's take a look at how they work together to light up the Internet.

The Scientific Breakthrough

[1] *Advanced Optical Communication systems and Networks*

"For the rest of my life, I will reflect on what light is,"[2] Albert Einstein wrote as he puzzled over the interaction between matter and energy. His thought process, along with those of several colleagues, gave rise to Quantum Mechanics, the explanation of existence at the most refined level. NTT optical physicist Shoichi Sudo called it "the most successful theory yet devised by the human mind." [3]

Judging that success by its impact on human progress, that case would be difficult to argue simply because, without Quantum Mechanics, there would be no computers, no mobile phones, no TV nor any other electronic product. In fact, Quantum Mechanics undergirds the two main technical planks of the modern age: the Integrated Circuit -- the processor for every computer, and the Optical Amplifier -- the power of the communication networks at the core of the Internet.[4]

The story of the integrated circuit has been well described; after all, the computer industry has never been accused of being shy. Telecom infrastructure firms, on the other hand, not given to Silicon Valley-style hype, have left the optical amplifier a bit of an unpromoted orphan of unknown genealogy. And yet it "is one of the most attractive and fantastic quantum electronic products to appear in technology, in particular, for optical communications."

Let's take a look at that geneology. The Quantum Mechanics of light stimulation -- part of Einstein's "thinking about what light is" -- was first articulated in his 1917 paper, *On the Quantum Theory of Radiation.* His complex formulas belie the fact that light amplification is conceptually simple: atoms can be excited to emit additional photons thereby amplifying light. This stimulated emission produces a beam of a single frequency or wavelength of light, in contrast to the spontaneous emission of a broad

[2] Perkowitz, Sidney, *Empire of Light*, 1999.
[3] Sudo, Shoichi, *Optical Fiber Amplifiers, Materials, Devices, and Applications,* Artech House 1997 pg. 8
[4] Note: The first practical IC was developed by Robert Noyce at Fairchild Semiconductors based on the p-n junction invented by Kurt Lehovec at Sprague Electronics.

spectrum of 'colors' of light from the Sun. However, turning Einstein's scientific conception into usable technology and then into practical products, and finally, into the power of the Internet was not easy.

In fact, it took forty years from the time Einstein conceived of quantum equivalence before a Columbia University student named Gordon Gould realized how to use it to make light amplification practical. On the night of November 13, 1957, Gould bolted upright in his bed with a revelation about how to make Light Amplification by Stimulated Emission of Radiation, the LASER. That night Quantum Electronics was born.[5] His Columbia Professor, Charles Townes, and several others played a role in this landmark innovation, but it was Gould, in the end, who obtained the "four basic laser patents that had been tested in every imaginable way…(to seal) Gould's reputation as the real inventor of the laser."[6]

Optical Amplifiers

On the day of his epiphany, Gould understood the importance of Light Amplification.[7] In fact, only by narrowing his laser claim to just that optical amplification aspect did Gould receive a key patent -- the Optically Pumped Laser Amplifier USPTO #4,053,845, (a continuation-in-part of the patent originally filed in 1959). He realized that his laser might be used for communications, and with that in mind, in 1972 he co-founded an optical telecom firm, the aptly named Optelecom Inc. There "Gould worked on the company's optical communications system contract," his first optical networking job.[8]

By that point, scientists at Corning Glass had demonstrated fiberglass optical cable pure enough to be used for transmitting data, but their fiber

[5] Sudo, ibid.
[6] Taylor, Nick; *Laser* pg. 284
[7] Hecht, Jeff, *Beam: The race to make the laser,* Oxford University Press. pg. 50.
[8] Taylor, Nick, *Laser.* pg. 197

could not be mass produced — until years later when Bell Labs researchers perfected a chemical vapor deposition process. As a result, during its formative years, Optelecom was forced to hand-spin its own fiber by using torches fueled by hydrogen tanks in the basement of Gould's employee (while his children slept upstairs no less)![9] With these hand-made optical fibers and optical amplifiers, the "objective of Gould's inventiveness became finding ways to combine the new field with the information needs of various industries and agencies."

Thus Optelecom became the pioneering optical networking company.

Pursuing products in the quantum field, Gould created "systems and devices that rely on the interactions between light and matter such as lasers and optical devices used for optical amplification and wave mixing."[10] Soon enough, he and his Optelecom colleagues, with a prescient view toward the possibilities of wave mixing, invented a multiplexer using "optical fiber as a light pipe," (USPTO #4,268,116A). With the "capability of carrying approximately 1000 or more television channels," wave mixing on different frequencies, known as wave division multiplexing or "WDM," became a development goal for Optelecom as the 1970s drew to a close.

Optical Steroids

To work on this and related projects, an engineer with a PhD from Brigham Young University named Dr. David Huber beat a path to the east coast to work with Gould at Optelecom in 1983.[11] Raised in the lumber and forestry town of LaGrange Oregon, Huber became head of Light Optics Research at Optelecom as he sought to light up more than one light

[9] Taylor, Nick. Laser. P 209.
[10] Bahaa E. A. Saleh, Malvin Carl Teich, "Fundamentals of Photonics" preface xxii, John Wiley & Sons, Feb 27, 2019
[11] Optical amplifiers for video distribution - Huber - 1990 - International Journal of Digital & Analog Communication Systems - Wiley Online Library

path inside the fiber at a time. However, he needed more capital than Optelecom would provide, so he went to work at General Instrument Corporation where he invented two components for his WDM system -- a tunable erbium optical amplifier and a spontaneous emission pump to turn his lasers on and off for years without fail. When his department at GI was shuttered, Huber returned to Optelecom.

The CEO of Optelecom introduced him to me a few weeks after the free release of the World Wide Web. Then on November 13, 1993 -- exactly 36 years to the day after Gould's invention of the laser and optical amplifier -- Optelecom, Huber and I, chartered a new venture to build massive-scale WDM systems powered by optical amplifiers. Optelecom took an equity stake in the startup in return for managerial, financial and production support[12] with a plan to, as Optelecom CEO William Culver explained in *The Baltimore Sun,* "expand the capacity of cable systems to 50,000 channels,"[13] — far beyond the 1,000 channel aspiration previously held by Optelecom.

To reach that goal, the startup used a special kind of optical amplifier, the erbium-doped fiber amplifier (the "EDFA"), invented by researchers at the University of Southampton in England and Bell Labs in the U.S.[14] Their EDFA amplified light waves inside the fiber itself to perpetuate the natural immortality of light signals that would otherwise dissipate while traveling in the glass fiber. The first generation of erbium amplifiers were not acceptable to Huber who consequently invented an erbium optical amplifier that boosted all the signals carried on a fiber simultaneously -- receiving his patent[15] just months before the new venture was chartered. So important did we consider this innovation that, for a brief period, I

[12] Business Briefs - The Washington Post. May 17, 1993.
[13] Auerweck, Steve. The Baltimore Sun. Optelecom, HydraLite become partners
[14] Greenemeier, Larry. Scientific American. "Millenium Foundation Recognizes Inventors and Technologies that Changed the World" April 8, 2008
[15] Huber, David. "Low Noise, High Power Optical Fiber Amplifier" USPTO# 5,140,456. August 18, 1992.

called their startup "Erbium Networks," before the team settled on the name Ciena Corp.

Wave Division Multiplexing

In our business plan, we made some bold statements:

> "Using these core technologies in its proprietary architecture, the Company believes that it currently has the equipment to optimize the capacity of the fiber optic networks envisioned by today's telephone and cable TV companies. The Company believes that its approach represents a quantum shift which will permit full utilization of the "data superhighway" and that it is *leading the paradigm shift in communications.*"

Forbes magazine writer Toni Mack described, in the very simplest terms, the initial steps taken to bring about that paradigm shift: "Huber started with a laser...then Huber added a device called an optical amplifier."[16] Of course the system was infinitely more complicated than that. For example, Ciena had to develop a first-of-its-kind *dual-stage* optical amplifier to correct for the dispersion of the different multiplexed frequencies as they traveled long distances. This breakthrough enabled 16 parallel waves to travel arbitrarily long distances in the fiber. Thus Ciena delivered the first commercial dense WDM system, ('dense' referring to more than four light waves or 'lanes').

You might think of WDM as optical amplification on steroids for it amplified a multiple number of fiber lanes. As a result of this efficiency, WDM required much less power and dissipated much less heat than electronic systems. In addition, WDM kept switching and routing as well

[16] Mack, Toni. "Communications: the next wave." Forbes. October 6, 1997.

as network restoration in the optical domain. These advantages were so far reaching and consequential that the authors of *Advanced Optical Communication Systems and Networks* wrote: "The introduction of WDM signaled a real start to optical networking."[17]

Ciena's role in that start was highlighted during the Centennial of The Optical Society of America. Their decade-by-decade recounting of the 100 year history of the OSA, a series called Centennial Snapshots, captured the major event, personality or trend in each 10-year period following Einstein's Quantum Theory paper. Their trend for the 1990s was how "breakthroughs in fiber optics and networking transformed society and laid the groundwork for the global Internet." Two personalities in that Snapshot were Huber and myself since I considered the pivotal event: "that first commercial DWDM system was the 'real dawn of the Internet.' "[18]

As the paradigm shift in network design proceeded, a broad range of amplifiers emerged because "most optical communication systems use{d} optical fiber amplifiers for signal amplification."[19] Looking into a modern telecom network, you would find for instance, the dual-stage amplifiers required for long-distance chaining and signal regeneration; you would find innumerable semiconductor amplifiers (and lasers); you would find Raman amplifiers and also *hybrid* Raman/EDFA amplifiers. But of this extended family, the "erbium-doped fiber amplifiers…[were] the most commonly used for supporting dense wavelength division multiplexing systems,"[20] so ubiquitous that, as WDM became the "technology of choice in the optical networks," the erbium amplifier became "the optical amplifier of choice for WDM applications."[21] [22] Thus "in both "conventional and wavelength division multiplexing systems and

[17]Cvijetic, Milorad and Djordjevic, Ivan, *Advanced Optical Communication Systems and Networks*, Artech House, 2013
[18] Hecht, Jeff. *The Optical Society and Optics & Photonics News (OPN).* "OSA Centennial Snapshots. Boom, Bubble, Bust: The Fiber Optic Mania."
[19] Dutta, Niloy K, *Fiber Amplifiers And Fiber Lasers*, World Scientific, Nov 14, 2014 p. vi.
[20] Chadha, Devi. "*Optical WDM Networks.*" Wiley Publishing 2019. pg.8.
[21] Chadha, Devi, ibid. Pg. 40.
[22]Agrawal, Govind P., *Fiber-Optic Communications Systems*, John Wiley & Sons, Inc., 2002.

networks," optical amplifiers became "the most important optical components."[23] The power from these amplifiers made WDM "the common basis of all local, regional, metro, national and international communications systems."[24]

Many firms played a role in this paradigm shift -- Lucent, Alcatel, Cisco and Huawei stand out -- however, because it was founded by the first optical networking company and its head of Light Optics Research, Ciena was the leader of the high-capacity optical pack. Starting with the Dawn, the very beginning of the optical quantum shift, Ciena continued to lead the way in optical networking. In one astounding example of nearing its goal of "full utilization of the data superhighway," the Melbourne Australia system from Ericsson and Ciena could transmit the equivalent of 1.2 million 4K ultra high definition videos per second over a single fiber!![25] Deployments such as this solidified Ciena's position as the top-ranking optical networking innovator and supplier, and the #1 vendor of optical systems the world.[26]

Thus a quarter century of planetary-scale telecom transformation was powered by applications of Gordon Gould's principle of optical amplification, and yet, despite its all-pervasive impact, only a handful appreciated it. One was technology futurist George Gilder who wrote in 1997: "Popularized by Ciena Corporation…..Lucent and Alcatel...the all-optical amplifier…is an invention comparable to the integrated circuit." He publicly predicted that the optical amplifier would make "possible a new global economy of bandwidth abundance."[27] His position was supported by *Building the Global Fiber Optics Superhighway* author David Chaffee who wrote: "As Gilder correctly points out, the reason that WDM

[23]Nemova, Galina. *Optical Amplifiers.* pg.135
[24] Grobe, Klaus and Eiselt, Michael. "Wavelength Division Multiplexing: A Practical Engineering Guide." John T Wiley & Sons. p. 2. October 2013.
[25] Saarinen, Juha, "Telstra, Ericsson and Ciena achieve world's fastest speeds on the Telstra transmission network in Melbourne." ITNews, January, 24, 2018.
[26] IHS Markit Vendor Scorecard. Optical Network Hardware. August 23, 2019.
[27] Gilder, George, Fiber Keeps Its Promise, Forbes ASAP, April 7, 1997 and Gilder Technology Report Feb. 1997.

was able to take off was the advent of the all-optical amplifier."[28] In addition, Soichi Sudo made a similar prediction (in the same year that Gilder made his) but took it one step further. Sudo foresaw how the optical amplifier would "usher in a worldwide revolution called the "Information Age."[29] Gilder and Sudo, in short, correctly predicted that the optical amplifier would power the infrastructure of the 21st Century.

By rejuvenating light throughout our global fiber glass web, light amplification turned Einstein's perplexing reflection into the all-pervasive power of the Internet. So as we celebrate the 50th of the Internet, let's also celebrate a 60th Anniversary as well, for 60 years ago the laser and the optical amplifier were patented and our world began to brighten.

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[28] Chaffee, C. David, *Building the Global Fiber Optics Superhighway,* Springer, 2001.
[29] Sudo, Shoichi. "Optical Fiber Amplifiers: Materials, Devices and Applications." Preface p xi.