How it works

OPTICAL AMPLIFIERS LITERALLY PUMP UP THE (PHOTON) VOLUME

Long an innovation confined to the laboratory, the all-optical amplifier opens the way to practical fiber-optic multiplexing without the complexities of per-channel regeneration and optical-to-electronic conversion.

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An advanced technology often languishes as "a solution looking for a problem" until it eventually meets up with a corresponding problem that's looking for a solution. Optical amplifiers and multiplexed fiber-optic signals are an excellent example of such a pairing. The high-capacity fiber-optic links installed by telephone and networking companies during the last decade had far more gigabit-per-sec capacity than most applications needed. But now that the many demands on fiber capacity have grown at spectacular rates and have saturated the fiber's capacity, system designers must devise ways to increase channel capacity.

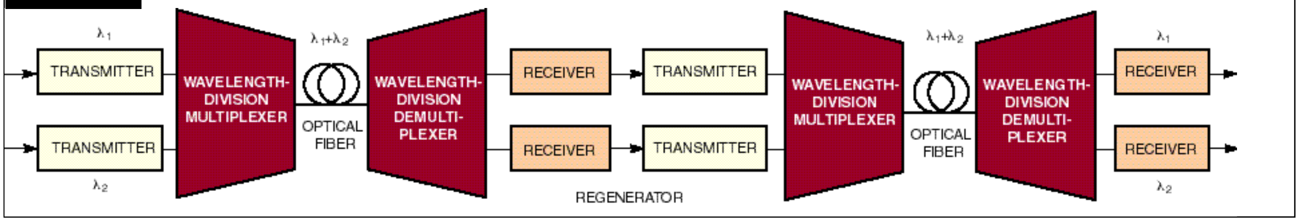
The obvious way to increase channel capacity is to install more fiber, but this technique is undesirable because it is costly and disruptive to all but the shortest links. Your second choice is wavelength-division multiplexing (WDM), a process that multiplexes several independent optical signals onto the same fiber. In WDM, you combine different optical wave-

WHAT COLOR IS YOUR BIT STREAM?

Wavelength-division multiplexing (WDM) relies on the simple fact that electromagnetic wavelengths—in this case, optical ones—that share a common medium do not interact with each other, just as red- and green-light beams do not mix when you shine their beams through each other. To make WDM commercially practical, you need standards defining the operating wavelengths so various vendors' multiplexers, demultiplexers, and associated components will be compatible and interoperable. ITU-T Recommendation G.692, "Optical Interfaces for Multichannel Systems with Optical Amplifiers," defines WDM systems with four or eight channels, each operating at maximum bit rates of 2.5 Gbps for the OC-48/STM-16 standard. A revised version of this recommendation will cover 16- and 32-channel systems, each at 10-Gbps OC-192/STM-64 rates.

Because the overall optical window is fixed, you need closely spaced channels, which is like having slightly different shadings of the same basic color optical signal. The dense WDM spacing of G.692 uses a wavelength grid centered on 1552.52 nm, corresponding to a frequency of 193.1 terahertz (1 THz=1000 GHz), and with channel spacing of 20 nm/100 GHz (it's hard to believe that it's the channel *spacing*, not the overall band!). There are 43 evenly spaced channel assignments over the range of 191.7 to 195.9 THz (1563.86 to 1530.33 nm). The industry has plans to halve spacing to a mere 50 GHz and to provide twice as many channels in the optical-transmission window.

FIGURE 1



Electronically restoring signal strength in one optical fiber carrying multiple signals requires multistep demultiplexing, optical-to-electronic conversion, amplification, and their reverse processes.

lengths (essentially, different colors) using optical filters made of in-fiber Bragg gratings, and the single fiber carries these wavelengths as independent, noninteracting photon streams. The result is a gain in the fiber's capacity by a factor of 2, 4, 8, 16, or more (see **sidebar** "What color is your bit stream?").

But there's a serious drawback to WDM that has limited the technique's application, in addition to the inherent complexities of optically multiplexing and demultiplexing optical signals. Amplifying optical signals to compensate for unavoidable losses in the fiber is a multistep process (**Figure 1**). You need to optically demultiplex the wavelengths using costly optical filters; go through an optical-to-electronic conversion for each signal; use electronic regenerative amplifiers and reclocking circuitry; reconvert from electronic-to-optical form; and then perform the complementary multiplexing operation again. This process can easily negate the advantages of using one fiber to carry multiplexed optical signals, and a complete amplifier stage costs $50,000 to $100,000 for just one channel.

So, who needs electronics?

Enter the optical amplifier, also called the optical-fiber amplifier (OFA)—and no, it's not an "op amp" for short. Using advanced and subtle principles of atomic physics, this amplifier neatly solves the amplification problem for nonmultiplexed signals as well as for multiplexed optical signals that have differing data rates, jitter, and waveshapes in the same fiber. The beauty of the OFA is that it closely approximates a photon pump, multiplying the volume of photons by a constant factor without regard to the photon's underlying timing or frequencies. OFAs are no longer lab devices, either. Vendors such as Lucent Technologies (www.lucent.com/micro/opto), Ciena Corp (www.ciena.com), Pirelli Cables and Systems (www.pirelli.com/cables), and Hewlett-Packard (www.hp.com) are supplying them to OEMs and installing them in long-haul optical-fiber links.

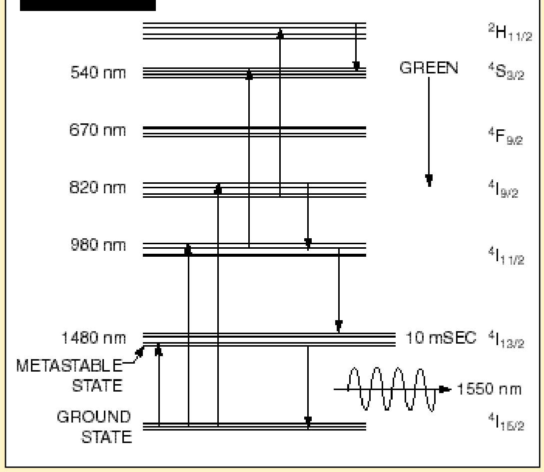
The optical amplifier is analogous to a highly linear electronic amplifier that functions as a gain block and transparently boosts the amplitude of an input signal—whether that signal is one pure tone, multiple tones, complex music, or random variations—without any need for the amplifier to judge or understand the nature of the input signal. Just as you do with a linear amplifier, you can change the signal you present or increase the signal frequency up to the amplifier's maximum capability without changing the OFA itself. You'll endure a very different situation when you try to upgrade signals passing through an optical-to-electronic-to-optical regenerator.

Because of various solid-state physics constraints, OFAs currently operate effectively in the third optical-transmission window of 1530 to 1565 nm (1.530 to 1.565 mm). This wavelength window is commonly used for long-haul fiber links. OFAs are now less prac-

ENERGY STATE TRANSITIONS YIELD PHOTONS

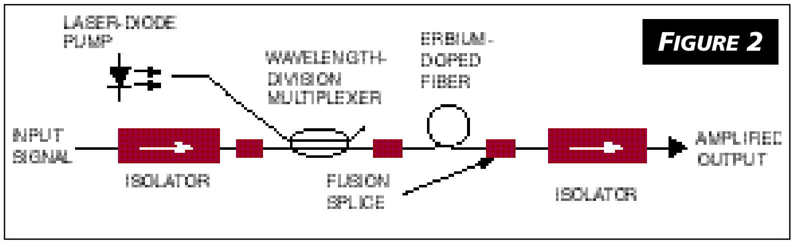
To produce more photons (optical amplification), you need to excite the erbium ions in the optical fiber to a higher energy metastable state than their initial ground energy state (**Figure A**). To excite the ions, couple about 20 mW of laser-diode pump light into the erbium-doped fiber (pump wavelengths of 980 and 1480 nm are common). The ions in the fiber then absorb this pump-light energy and are excited to their metastable state. They transition back to their ground state either by *stimulated emission,* which produces the desired photon amplification, or by random *spontaneous emission* after about 10 msec.

FIGURE A



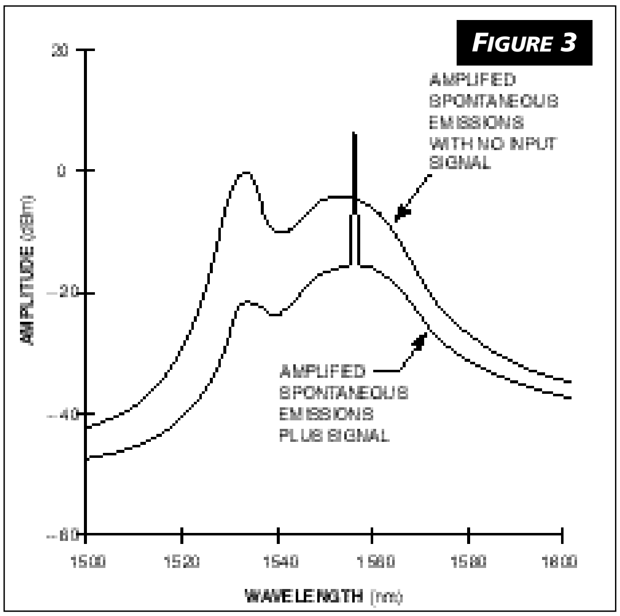
Optical-fiber-amplifier operation is based on erbium-ion energy levels and stimulated transitions between these levels.

tical for the first optical window, centered on 860 nm, and the second window, centered on 1310 nm. You use the second window for shorter distance cable TV and LANs; at this shorter range, there is less need for amplifiers.



A complete OFA uses a laser-diode pump to combine new photons with the input signal in a specially doped fiber; the optical isolators prevent unwanted secondary effects (adapted from *Hewlett-Packard Journal*, with permission).

An OFA comprises a laser-diode pump; a WDM; a waveguide made of silica-based fiber about 70m long and with a high concentration of erbium atoms (that's why an OFA is also referred to as an EDFA, for erbium-doped fiber amplifier); and optical isolators (**Figure 2**). In operation, the fiber signal to be amplified goes through the input isolator and is multiplexed with excited erbium ions that are coupled into the fiber at the WDM. This meeting of the input-signal photons and the excited erbium ions causes stimulated emission in the fiber of more photons, which are identical to the photons of the input (see **sidebar** "Energy state transitions yield photons"). The result is amplification, but instead of increased voltage—the conventional measure of signal amplitude—optical amplification increases the *number* of photons, which is driven by the input wavelengths and the relative quantity of photons in the input stream.



The output spectrum of an erbium-doped fiber amplifier shows the amplified spontaneous emission (ASE) and the reduction in ASE, plus desired signal gain that occurs when an input signal is present (adapted from *Hewlett-Packard Journal*, with permission).

The isolators keep internal reflection under control for two reasons. First, these reflections can cause an undesired "lasering" effect. Second, they can contribute to the generation of excess, undesirable photons via amplified spontaneous emission (ASE). When there is no input signal, the OFA produces these random emissions as the stimulated ions decay to their ground energy state. These spontaneous emissions have an overall spectral energy density that corresponds to the statistical distribution of energy bands in the erbium atoms, with most of the energy concentrated across a spectral range of about 40 nm (**Figure 3**). The critical ASE problem is that the spontaneously stimulated photons can travel along the fiber and create additional photons in a cascade effect, with ASE magnitudes of 0 dBm or more at the amplifier output.

Although ASE is undesirable and is partially minimized by the isolators that shield the amplifier from the reflections, the operation of the OFA with an input signal actually improves the ASE situation. With an input signal applied to the OFA, many of its potentially spontaneous emissions from the fiber are instead stimulated by photons from the laser (this reminds me of the ancient FM "quieting" effect, in which signals that are greater than a threshold value suddenly diminish the FM-channel background noise to an inaudible level!). The result is both the desired signal amplification and a reduction in ASE by about 10 dB. OFAs have typical optical gains of 30 dB and output in the 10-mW range, although both figures are increasing. Although their cost is about 50% higher than one electronic/optical regenerator channel, OFAs remain attractive because they handle multiple channels and upgraded data rates without difficulty. e

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