

New semiconductor-like, planar manufacturing technology will improve the performance and decrease the size and cost of optical amplifiers.

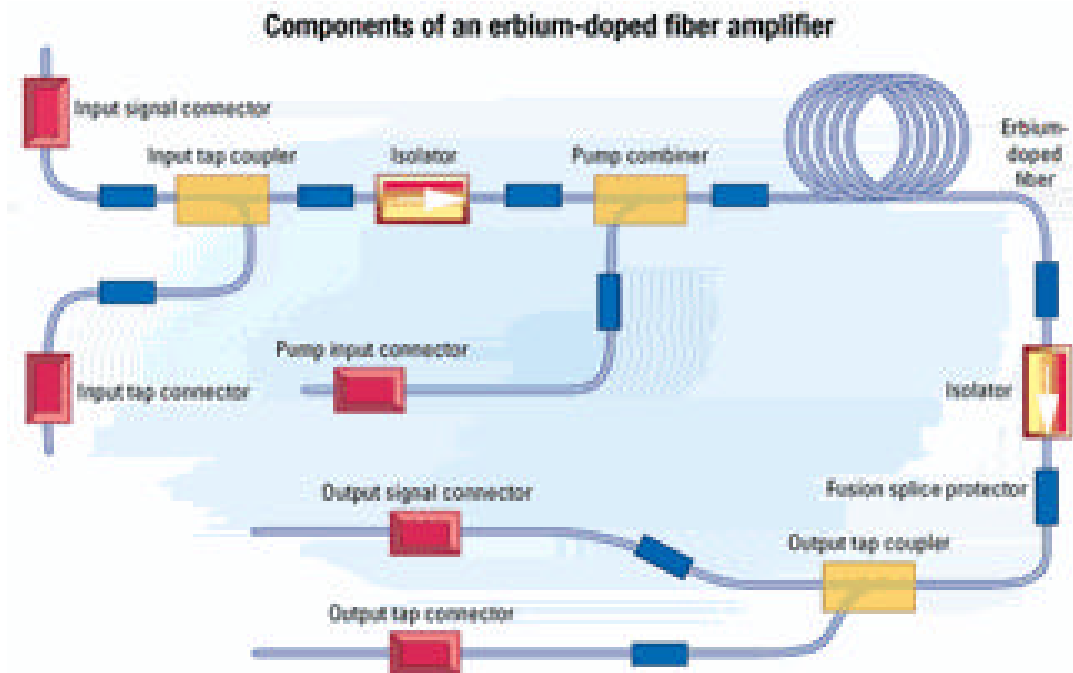
DR. JOYCE KILMER, Symmorphix

Large-scale core and long-haul infrastructure build-outs drove the growth in optical networking during the last five years. The market recovery, however, will occur because of additions in incremental capacity and the expansion of metro/access networks.

Unlike the earlier expansion, which was largely fueled by lower-cost implementations of mature fiber-based discrete components, new growth will follow the development of a new class of photonic integrated components. Over the next year, these components will move from research and development into production. That is due to advances in semiconductor-like manufacturing technology that employs physical vapor deposition optimized for photonics and the development of mass production techniques that monolithically integrate active and passive components on a single planar waveguide.

By embedding optical amplifiers with a variety of passive components, this new component class known as amplifying photonic integrated components (APICs) offers numerous benefits to system manufacturers and carriers. APICs promise significant performance benefits. Historically, planar waveguides have not delivered performance comparable to fiber-based discrete components, primarily because of higher insertion loss. A planar-waveguide amplifier or APIC can compensate for this liability and consequently serve as a fundamental building block for a new generation of optical components—much like the integrated operational amplifier or "op-amp" for semiconductor ICs. APICs also offer developers a smaller form factor, because these components do not require extensive packaging and fiber interconnects—unlike fiber-based discrete components.

Long term, APICs promise cost benefits, some of which come from monolithic integration. Planar waveguides can also serve as a type of silicon optical bench (SiOB) for hybrid integration, by eliminating discrete packages and the fiber-base for functions that aren't possible to integrate monolithically. That is accomplished through monolithic integration of serial and parallel functions. The input tap, pump multiplexer, and output tap are serial functions that can be monolithically integrated, while arrays of amplifiers are examples of parallel integration. Developers can also reduce costs by integrating a hybrid of the laser-diode pump sources and embedding amplifiers with other functions such as switching and wavelength multiplexing.



A single-stage erbium-doped fiber amplifier requires 21 discrete components

Finally, APICs offer architectural benefits to systems developers. At the systems level, low-cost optical amplifiers (OAs) promise to serve as the linchpins that electronic amplifiers were in the microwave industry. Microwave system developers quickly learned the importance of amplifying the signal early and often-before the signal-to-noise ratio (SNR) had a chance to degrade. In photonics, developers may follow a similar strategy, sprinkling compact, low-cost OAs throughout the network to compensate for "node losses" in optical crossconnects, optical add/drop multiplexers, metro transport, access splitters/demultiplexers, and compensation and transceiver modules.

Better performance, tighter integration

To ensure success, APICs must offer performance advantages as well as higher levels of integration. OA performance requirements vary widely. Gain, for instance, can range from 10 to 20 dB, noise from 7 to 5 dB, and output power from 0 to 20 dBm. The common requirement across these applications, however, is low polarization sensitivity.

From an integration perspective, an OA is in essence one of the first examples of a quantum mechanical machine. A machine is a collection of parts with different functions that work together; in optics, some materials perform certain functions better than others. Since these different materials are typically incompatible from

a manufacturing standpoint, developers had to separate them by free-space or optical fiber to get the "optical machine" to work. Consequently, this approach led to expensive collections of discrete components "cobbled together" either by micro-optical positioning or by fusion splicing of fiber pigtailed packages.

Established OA technologies such as semiconductor optical amplifiers (SOAs) and erbium-doped fiber amplifiers (EDFAs) failed to achieve this ideal combination of performance and integration. While developers have continually attempted to boost performance in SOAs since the 1970s, they faced significant difficulties in reducing noise figure, polarization dependence, cross-phase modulation, and gain ripple, while in creasing saturated output power. Furthermore, SOAs are typically fabricated from indium phosphide (InP), an III-V crystalline material. While these crystalline structures are efficient at making lasers for optical sources, it's difficult to keep the same crystalline structure from naturally lasing and operating as a traveling wave optical amplifier.

EDFAs bring their own limitations. Since the early '90s, erbium (Er) has been the reliable workhorse of the OA business. Virtually all the carrier-grade OAs in use today are Er-based, because it is the most natural technology for achieving optical amplification. The intrinsic spacing of the Er atom's "manifold" of Stark split levels are perfectly arranged to give a 15xx-nm band of optical amplification when optically pumped by either a 980- or 1480-nm pump laser.

The noise figure in Er-based waveguide amplifiers is inherently lower than SOAs for three reasons:

- ?? The Er-based waveguide's mode size matches well with the input-signal fiber. SOAs, in contrast, feature small waveguides that correspond to a high input-signal coupling loss, which degrades unamplified SNR.
- ?? The Er ion energy scheme is not plagued with a large number of excited state levels and consequently generates less noise during amplification compared to an SOA.
- ?? Er-based waveguide amplifiers do not generate cross-phase modulation, which is a primary noise source in SOAs.

To date, the use of erbium for optical amplification is limited to optical fibers, because Er is the only rare earth that can be doped, then processed into silicon oxide (SiO₂)-based glass optical fibers. But in fibers, Er concentrations must be kept very low to prevent upconversion, forcing the EDFA's fibers to be long in length—many meters for C-band operation and even longer for L-band applications. Attempts to create shorter fibers or waveguides by putting large amounts of Er in the glass typically have been limited by cooperative upconversion (C_{up}), which occurs when the ions get so close that they "see" and trade energy with each other rather than with the signal to be amplified (see sidebar, "Upconversion tutorial"). This characteristic limits the integration potential of EDFAs. Typically configured as modules, EDFAs are "cobbled together" with other discrete components or modules to achieve higher levels of

integration (see Figure).

The ideal APIC brings together Er-doped amplifying materials to achieve the application's required performance and low-loss passive materials to maximize integration. Furthermore, these Er-doped amplifying materials should allow Er ions to exist in the highest concentrations possible without resulting in up conversion. That would support the development of centimeter-length rather than meter-long waveguide amplifiers.

Manufacturing considerations

The optical manufacturing process will hopefully produce materials with a controllable index of refraction with excellent uniformity and repeatability, low stress, and birefringence, which contributes to low polarization dependence and temperature insensitivity to withstand the multiple inevitable temperature cycles encountered during manufacturing and reliability testing. The key lies in the nature of the material and the fabrication process used. To simultaneously achieve all these attributes, several manufacturing technologies were developed over the years to produce planar-waveguide components.

The first technology developed was flame hydrolysis deposition (FHD). Employed by some manufacturers today in the manufacture of passive planar waveguides, FHD uses a flame to deposit soot, which is subsequently consolidated or melted. This process is repeated until the desired thickness is achieved. Dopants such as boron (B), phosphorus (P), and germanium are used to modify the melting point and control the index of refraction to form the waveguide.

The challenge for manufacturers using this technology lies in controlling the index and compositional uniformity as well as film stress. The latter issue is particularly troublesome, because each layer is deposited with a different composition than the previous layer, which leads to different material properties. One of those properties is the coefficient of thermal expansion (CTE), which mismatches lead to stresses in the films. The dopants tend to be mobile so not only are stresses difficult to control, they change over time and operating conditions. Stress in turn leads to birefringence, which causes polarization dependence-high polarization-dependent loss/polarization-dependent gain (PDL/PDG) and polarization-mode dispersion (PMD). Stress also leads to wafer bow, which affects the co-planarity of waveguide facets coupling to fiber arrays. The misalignment to fiber and any changes over time and operating conditions, combined with index non uniformity, pose severe manufacturing and reliability challenges.

Moreover, because FHD is inherently a high-temperature process, it limits material possibilities. Any film composition must be formed as the by-product of a chemical reaction in an oxygen-hydrogen (OH) flame. Dopants such as erbium, for which gaseous compounds aren't readily available, must be introduced using a liquid form through bubblers. The high-temperature flame causes Er clustering, while the use of bubblers and repeated soot/consolidate steps create

compositional nonuniformities. In addition, the OH flame adds OH hydroxyls, which limit its use for the amplifier's S-band and generally increase absorption loss in the C-band. Longer term, FHD is unsuitable for any integration with electronics functions in the substrate, because the large thermal budgets and threshold-voltage shifting dopants (B, P) associated with the process would alter device performance.

Recognizing the limitations of FHD, some manufacturers have imported a chemical-vapor deposition (CVD) process from the semiconductor industry. CVD, particularly plasma-enhanced CVD (PECVD), is also used today to produce passive planar waveguides. The challenge is optimizing this process to route photons rather than electrons.

PECVD is a high-temperature process, which is typically used to manufacture passive components such as planar splitters and arrayed waveguide gratings (AWGs). While its deposition temperature of 300-400°C is much lower than for FHD, it often requires a densification reflow step, which can take one or more hours at 1,000°C to eliminate voids and outgas any incorporated H from the plasma reaction. Without reflow, the film exhibits high scattering loss from the columnar defects and voids, and the porous glass absorbs water, which would react with dopants such as P used to lower the melting point to permit the reflow.

Unlike FHD, which has the potential to form a thick film and fill deep structures in one step, PECVD typically requires four to five deposition/reflow repetitions. PECVD uses gas plasma that is by its nature nonuniform. While the semiconductor industry has worked diligently to achieve reliable center-to-edge dimensional uniformity, the photonics industry requires compositional uniformity as well. That is hampered by nonuniform pumping out of plasma reaction by-products. The mass transport of reactants and by-products is inherently different at the center of a wafer than at the edge. From an Er-doped OA perspective, the high temperatures needed during the densification stage clusters the erbium, leading to quenching loss. And like FHD, the use of these high temperatures and chemical dopants limit the possibility of the integration of other layers to create additional functions.

To make planar-waveguide amplifiers rather than simply passive planars, some manufacturers use ion exchange in glass. With ion exchange, the refractive index of bulk glass is changed by chemically diffusing ions such as potassium (K⁺), argentine (Ag⁺), and thallium (Tl⁺) into the glass while immersed in a high-temperature salt melt. Larger ions such as Tl⁺ can cause more local stress (hence larger index changes) but are corrosive and toxic. The bulk glass is formed in small slabs in high-purity crucibles such as platinum. The glass must cool very slowly to attain compositional uniformity and avoid large stress buildup, but the extended time at high temperature causes erbium to cluster and the small slab size yields few substrates, limiting volume production.

To make planar optical amplifiers, Er-doped bulk glass is sliced into substrates and cut into die, then bonded to similarly prepared undoped glass die to form

separate passive and amplifying sections. The bonding of different composition glass makes integration of multiple functions requiring different materials difficult. During the ion exchange process the K^+ or Ag^+ cation exchanges for sodium (Na^+) in the glass. This ion exchange is limited by the cation transport in the glass, the mass transport of reactants at the glass surface, and the kinetics of the reaction at the glass/melt interface. The melt is stirred and the used cation replenished. The completed waveguide that is formed near the surface is semicircular in cross section at best and has a graded-index profile. That leads to a non-circular waveguide with small index contrast into the glass but large index contrast at the air interface where roughness caused by the melt increases scattering loss.

There is further loss trying to couple an asymmetric waveguide mode to the fiber's symmetric mode. One way to reduce this loss is to use an electric field to drive the ions deeper and create a buried waveguide. But that adds significantly to fabrication time. For amplifiers, the erbium is not confined to the core as with deposited and etched waveguides, so signal light in the cladding is absorbed, since the pump light does not extend out as far. In addition, any asymmetry in the waveguide prevents the two peaks in vertical cross section of the signal and pump-guided modes from completely overlapping, further reducing the efficiency of energy transfer from the pump via Er to signal. Even for a buried waveguide, the index gradient creates a weakly guiding waveguide, which limits efficient energy transfer by reducing the absorption and emission profile overlap (or cross-product of the respective confinement factors), thereby requiring higher pump powers and cost. From a reliability perspective, the presence of P is undesirable, since it is a hygroscopic-forming phosphoric acid. This acid attacks the glass and changes its optical properties if the device is not hermetically sealed, while the mobile Na^+ ions required for ion exchange remain mobile within the Telcordia storage temperature range.

In contrast, perhaps the oldest, best-understood, and most reliable material deposition technology is physical vapor deposition (PVD) or "sputtering." In PVD, a solid source is used as an arbitrarily large-area target. The target facing a substrate, such as a silicon wafer, looks to the substrate as if it were "semi-infinite." That leads to extremely good dimensional and refractive-index uniformity, since it is based on solid source uniformity combined with vapor phase mixing rather than flames, plasmas, gas lines, mass flow controllers, bubblers, or pumping. In addition, a solid source provides compositional uniformity and reproducibility. The film is built up one atomic layer at a time by sputtered material arriving at high energy. The resulting films are dense, transparent, and free of light-scattering voids or morphology. For depositing upper cladding, the low-temperature, deep-fill capability is important, and the use of the exact same material for upper and lower cladding combined with low birefringence symmetric cross section waveguides create the most closely matched guided modes to match to fiber with low coupling loss.

PVD is a low-temperature process with very little temperature cycling during film

formation. There is no subsequent consolidation, reflow, densification, or de-gas step required. When a deposited film's CTE matches the silicon wafer substrate, low stress is built into the film stack, yielding negligible wafer bowing. That simplifies the task of aligning the chip to fiber arrays for higher-yield backend assembly as well as packaging. Not only are reduced stresses advantageous for minimizing polarization problems, the presence of film stacks, substrates, and packaging materials with matching CTEs creates more reliable devices that are less sensitive to temperature changes. Furthermore, if a material has no dopants such as B or P that migrate, it behaves in a thermo-elastic manner, in which physical and optical properties are highly reproducible after temperature cycling. That in turn improves manufacturing yield.

Most important, PVD is a production-proven process that has been available for years. Employed extensively in the semiconductor, flat-panel-display, disk-drive, and specialty-coating industries, the process is used in high-volume systems that run 6-, 8-, or 12-inch wafers and even larger substrates. By customizing the process-chamber hardware, the PVD process can be optimized to produce the desired photonics-optimized materials with semiconductor-like automated manufacturing. For amplifiers, this photonics-optimized PVD process helps reduce upconversion by getting the erbium mixed into the customized solid source targets, then transferred to the substrate at low temperature during the "physical" deposition. Such a process has demonstrated a C_{up} value of 4×10^{-18} cm³/sec, the lowest achieved using a high-volume PVD production process. Furthermore, this photonics-optimized PVD process has demonstrated extremely good index uniformity to the seventh decimal place and very low birefringence to the eighth decimal place. That capability is particularly important in the manufacture of low-loss and low PDL/PDG waveguides and complex interferometric structures such as AWGs.

Promising process

New manufacturing processes can significantly reduce the costs of optical components, subsystems, and equipment and justify the continued build-out of the optical network into metro and access networks. One of the more promising planar integrated photonics manufacturing technologies is PVD. This process has evolved to such a degree that it can now be used to manufacture perfect glass waveguides. Combining state-of-the-art photonics-customized PVD processes with the deposition of amplifying element Er, manufacturers can create symmorphous structures, which allow erbium ions to exist in optimal concentrations with minimal upconversion.

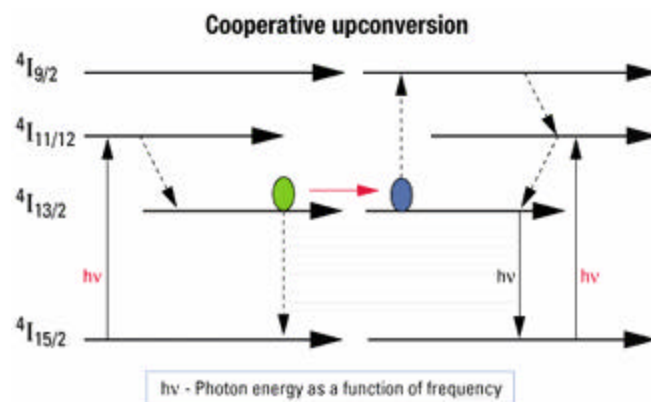
Photonics-customized PVD can produce a variety of ideal symmorphous materials for a wide variety of APICs. These components offer highly attractive cost savings by allowing developers to increase monolithic integration through the use of mixed-material systems, multiple structures, and multilayer and hybrid integration. Providing a path to more compact, lower-cost modules and systems, these devices will open the door to a new round of growth in optical networking.

Dr. Joyce Kilmer is director of application engineering at Symmorphix (Sunnyvale, CA).

Upconversion tutorial

In the cooperative upconversion process (see Figure), two erbium ions are first-order excited from the ground $^4I_{15/2}$ (first) level to the $^4I_{11/2}$ (third) level. These ions then quickly relax non-radiatively to the $^4I_{13/2}$ (second) level. One ion is then further excited into the $^4I_{9/2}$ (fourth) level while the other ion de-excites non-radiatively. The excited ion at $^4I_{9/2}$ then either relaxes non-radiatively back to $^4I_{13/2}$ or for some fraction is further second-order excited into the higher $^2H_{11/2}$ (seventh) and $^4S_{3/2}$ (sixth) levels, from which radiative relaxation results in the familiar green light associated with upconversion in erbium.

Typically, high pump power is required to compensate for the increased decay rate (shorter lifetimes at the $^4I_{13/2}$ level) to achieve inversion and high gain. The use of expensive high-power pumps eliminates the low-cost potential of planar-waveguide amplifiers. A high-volume production-capable process that can make low upconversion loss materials could enable the use of more cost-effective lower-power pumps.



The upconversion process in erbium (green light) typically requires high pump power to compensate for the shorter lifetimes at the $^4I_{13/2}$ (second) level.

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