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EXPLORING THE FRONTIERS OF OPTOELECTRONICS WITH FIB TECHNOLOGY

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A review of the current and potential future uses of FIB technology for the fabrication of optoelectronic devices and circuits is presented. The advantages of the maskless and resistless FIB fabrication are briefly reviewed. A DBR laser totally fabricated by FIB (both gratings and channel waveguide) is discussed as an example of FIB-fabricated optoelectronic components. The opportunities and challenges of future applications of FIB technology in fiber-optic communications optoelectronics are considered. In this application, components such as WDM laser sources, add/drop filters, waveguides, and combiners can be ideally fabricated in an integrated optoelectronic circuit by FIB.

A. Introduction to FIB Technology

The applications of photon-based devices are expanding at a dizzying pace as displays, communications and computing are converting to sophisticated "man-image" interfaces as well as utilizing the trasmission of ever greater and faster optical data. As shown in Fig. 1, the parameter space defined by the axes of electronic signal processing, optoelectronic conversion, and optical signal processing contains single devices ranging from lasers to detectors to waveguides, as well as various photonic integrated circuits (PIC) and optoelectronic integrated circuits (OEIC).

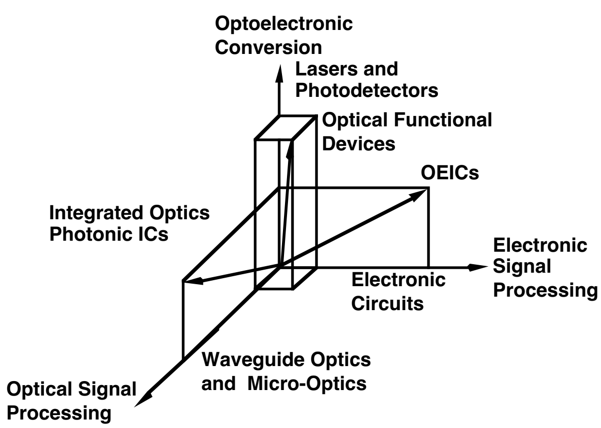

Fig. 1 Parameter space of optical function devices (after Wada and Crow[1]).

Most of the photon-based devices utilize compound semiconductors, with Si playing a minor role.Unlike Si digital integrated circuits, which deal with a single basic technology, photon-based devices cover not only a broad range of basic materials, but also require the development of different fabrication technologies for different applications. Focused ion beam (FIB) implantation is a maskless and resistless particle "beam" process[2], which can be applied with great versatility to the fabrication of optoelectronic devices. FIB micro- and nano-fabrication can be utilized to reduce the complexity required of conventional OEIC fabrication technology (in particular lithography, etching and implantation), which has to satisfy various requirements for different components fabricated on the same substrate.

FIB systems can provide an ion beam with a diameter ranging from a few μm down to ~10 nm. The focused ion beam is operated under computer control and can be placed on the sample surface with an accuracy equivalent to that of e-beam lithography systems using a laser interferometer driven stage. Since the focused ion beam combines energy, charge and mass in a single particle, FIB techniques for fabrication of optoelectronic devices include direct micromachining, maskless lithography, and implantation. The implantation approach accomplishes a certain functional aspect (usually charge carrier or photon confinement) of the device structure through the introduction of ions in order to provide either localized doping or ion-induced compositional mixing of multi-layer

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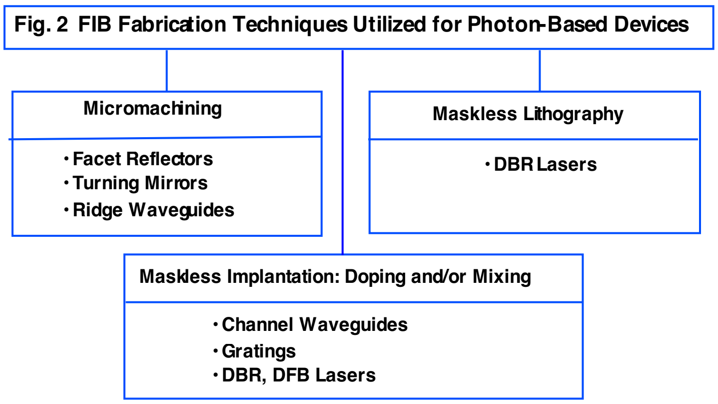
structures. In addition to being a high resolution maskless/resistless process, the FIB approach can readily adjust the implantation conditions (such as dose, energy, sometimes even species) in order to customize the process for each type of component during a single step.

B. FIB-fabricated Optoelectronic Components

FIB techniques have been used to fabricate various types of GaAs-based photonic and optoelectronic devices. Fig. 2 contains examples from each FIB fabrication approach. The examples range from mirrors fabricated by micromachining, to channel waveguides fabricated by mixing, to laser gratings fabricated by either doping, lithography or mixing.The fabrication of these devices by FIB has been recently reviewed by Harriott and Temkin[3] and by Steckl et *al.*[4] We have utilized primarily the mixing technique, wherein the FIB implantation of Si produces a localized region of much faster interdiffusion[5] of the Al in a $Al_{1-x}Ga_xAs/Al_{1-y}Ga_yAs$ superlattice upon thermal anneal. An important example is the fabrication of a DBR laser[6] by FIB mixing of superlattice/quantum well structures, as shown in Fig. 3. The FIB was utilized to fabricate both the gratings of the two distributed mirrors and the lateral confinement channel. The FIB mixing process utilized a ~70 nm diameter Si^{++} beam at an energy of 200 keV and a dose of 10^{14} cm^{-2}. The DBR grating period was 350 nm, designed to correspond to 3^{rd} order emission from the 30 nm wide quantum well. The mixing technique was also succesfully utilized to fabricate[7] relatively long (~1 cm) channel waveguides in a similar superlattice structure.



The main characteristics of the DBR laser under optical pumping consisted of several very narrow modes (1.5 Å), a coupling coefficient of ~ 50-80 cm^{-1}, coupling efficiency of 1.75-2.8, and a maximum mirror reflectivity of nearly 80-90%.

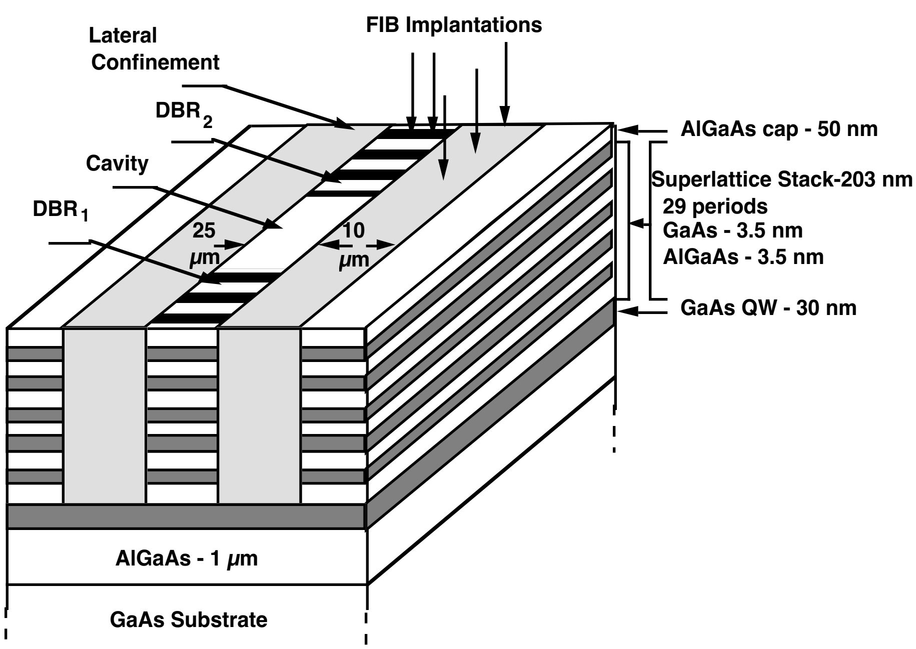


Fig. 3

DBR laser structure.

C. Future Applications

A major potential application of FIB technology will be in producing integrated optoelectronics for future fiber optic communications. Operation of optical communications channels takes place at the near-IR minimum (~1.55 μm) of optical fiber absorption. The Er-doped amplifier is the first step in the evolution of fiber optic communications, as shown in Fig. 4. At the moment, the enormous bandwidth capacity of fiber optics is highly underutilized. To increase effective utilization of communication networks, wavelength or time multiplexing components need to be further developed. In turn this requires new capabilities on the part of optoelectronic technology. For example, utilizing the wavelength division multiplexing (WDM) method requires the fabrication of laser sources with very precise control over the emission wavelength in order to provide closely spaced (1-5 nm apart) channels in the 30 nm window operating window. This represents an ideal application for FIB technology for several reasons: (1) one can easily and accurately increment the wavelength by computer programming the period of the grating ; (2) one can adjust each design to account for *local* variations in the value of the refractive index; indeed, without FIB, one would need to hold variations in n to ~ 0.1%; (3) one can fabricate new designs with rapid turn-around due to the totally maskless and resistless nature of the FIB process. A simple prototype of an integrated WDM module is shown in Fig. 5. This circuit, which contains three closely spaced (both spatially and in emission wavelength) DBR laser sources and a waveguide combiner, can be fabricated by FIB implantation in essentially a single process step.

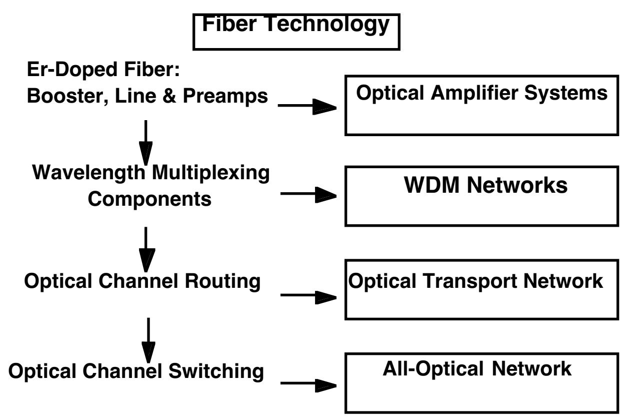


Fig. 4 Evolution of fiber optic communication.

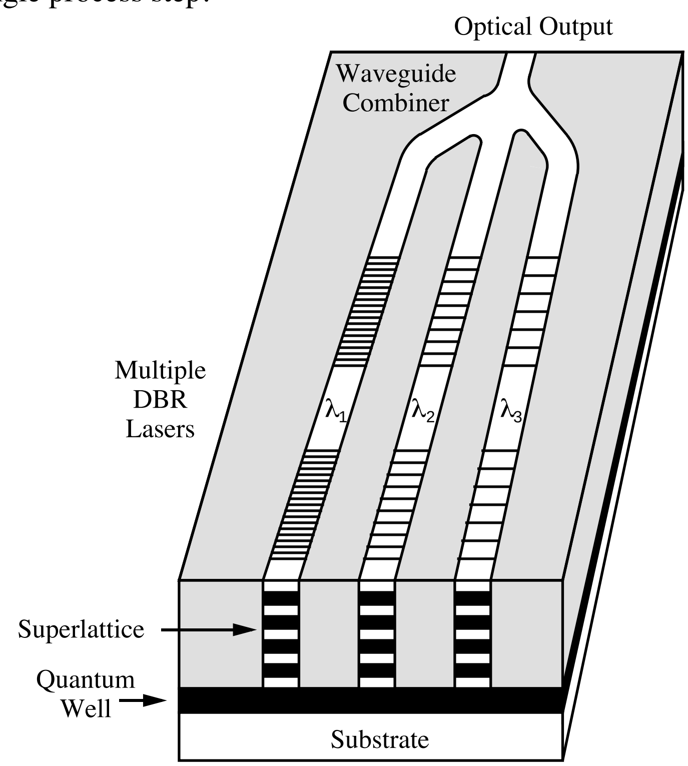


Fig. 5 Prototype of WDM module.

The next step in the evolution of fiber optic communication will include sophisticated optical channel routing and switching. A schematic implementation of such a circuit is shown in Fig. 6. This system uses WDM transmittters and receivers, Er-fiber amplifiers and add/drop filters. The latter are used to introduce new signals into the communication system, as well as to prevent their transmission past a certain location. In this system , most if not all all elements can be fabricated by FIB implantation. This includes the sources, the waveguides, the combiners, add/drop filters, and the optical switches. This shows the enormous appeal of this fabrication approach for the future of fiber optic communications cicuits.

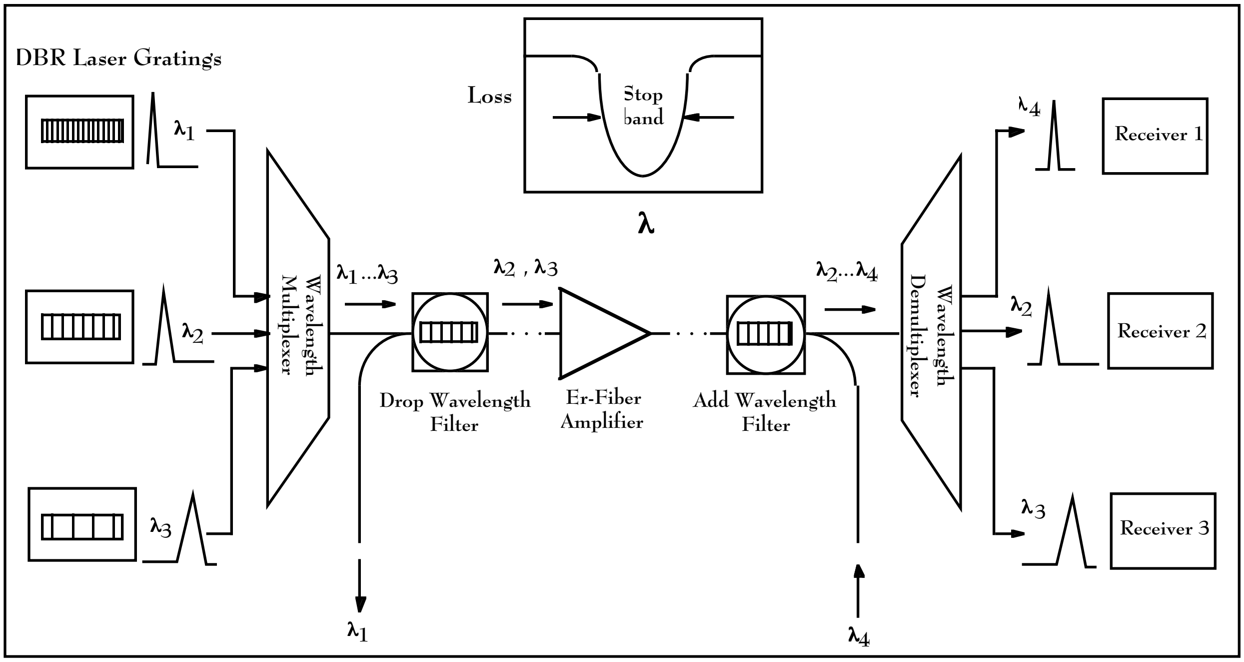


Fig. 7 A schematic diagram for a WDM-based fiber optic photonic system. The inset represents the generic stop-band spectral response of the add/drop filters.

D. Summary

In this article, I have briefly reviewed the potential future impact of a simple fabrication technology for optoelectronic and photonic devices and circuits based on focused ion beam implantation. In particular, I have explored the posibility of fabricating complex photonic circuits for fiber optic communications solely through the use of FIB implantation. The versatility and simplicity of this maskless/resistless process appears to render it quite attractive for such applications.

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