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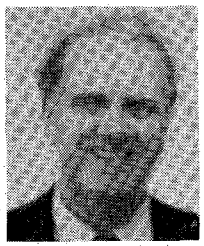

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The Birth of Lightwave Technology and Its Implications to Microwaves

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EVER SINCE the invention of lasers [1] in the late 1950's, the use of coherent optical radiation for communication and signal processing with multigigahertz bandwidth has been a major research goal in electron devices, microwaves, quantum electronics, and optics. In order to realize that goal, the key issues that need to be addressed include a) how to transmit optical radiation with low propagation loss and signal distortion, b) how to effectively interface optical devices with electronic devices, c) how to modulate, multiplex, switch, and detect optical radiation at such high data rates, and d) how to solve the materials and fabrication technology problems. In the early 1960's, research on optical communications was concerned primarily with transmission of laser radiation through the atmosphere and the pipes. These methods had numerous disadvantages, including atmospheric turbulence and system complexity. The initial work on low-loss optical fibers reported by Kao of the Standard Telecommunication Laboratories in England in the late 1960's [2], followed by intense research efforts at the British Post Office, Bell Laboratories, Corning Glass Works, Nippon Electric Company, Nippon Sheet Glass Company, Siemens, and AEG-Telefunken, finally produced a breakthrough in the early 1970's when Kapron, Keck, and Maurer of the Corning Glass Works announced the achievement of losses under 20 dB/Km in optical fibers hundreds of meters long [3]. The birth of the low-loss fibers added a new impetus to optical communication and signal-processing research. The advent of low-loss and low-cost multimode optical fibers means that inexpensive optical communications through fibers may soon be used, much as we now use coaxial cables, applied to existing, as well as future, communications needs. No longer is it necessary to have a large number of customers on a single transmission path in order

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to reduce the cost of the transmission medium to an *attractive* per-channel value. There is also no need to have the complexity of the apparatus associated with multichannel multicarrier systems. Communication through multimode fibers became attractive alternatives to coaxial cables, even in the megahertz bandwidth range.

The tremendous amount of research conducted in the 1970's laid the foundation for the understanding of fiber optics [4]. Research on the dispersive properties of the multimode fibers yielded both understanding on the limitation of the bandwidth of multimode fibers inversely proportional to the length of the transmission line [5] and the development of graded-index fibers to circumvent this limitation [6]. Much work has also been conducted to understand the loss mechanisms due to material absorption, material and waveguide scattering, radiation due to curvature, and cladding effects. It was found that Rayleigh scattering varies as $1/\lambda^4$, where λ is the wavelength, thereby limiting the usefulness of fibers for long-distance communications at visible light and shorter wavelengths. On the other hand, OH absorption peaks at 2.7, 0.95, and 0.72 μm are the major limitations of transmission loss at the long-wavelength range. Fig. 1 shows the loss measured by Miya *et al.* [7], broken down into the various contributions. The combined effects of scattering and absorption losses restricted the use of optical fibers for communications primarily to three wavelength windows centered about 0.85, 1.3, and 1.5–1.6 μm wavelengths. The need for both the purification of materials to reduce absorption and for the control of index profiles to reduce dispersion has led to a large amount of research work on the materials preparation and fabrication of fibers, using a diversity of techniques, such as double crucibles, chemical vapor deposition, preforms, annealing, etc. The need for sources and detectors at the 0.85-μm wavelength gave new impetus to the development of GaAlAs/GaAs heterostructure lasers for mode stabilization, long lifetime, and high-speed modulation [8]. The need for new sources and detectors at the 1.3- and 1.5-μm wavelength range has triggered research and the development of GaInAsP and GaInAs semiconductor lasers and detectors at these wavelengths [9], [10]. The 1.3-μm wavelength window is especially interesting because of the very large bandwidth in optical-fiber transmission that may be made available by balancing the mode dispersion with materials dispersion. The 1.5-μm wavelength window is especially interesting because the very low losses at that wavelength (~ 0.25 dB/Km) [11] may now allow long-distance transmission (e.g., undersea cables) with only a small number of repeater stations, a performance that far surpasses the capability of coaxial cables. Many practical and systems problems, such as how to splice or to interconnect fibers with low insertion loss, how to make fibers into cables with minimum added attenuation due to cabling, how to combine or distribute signals via star or other types of couplers, how to reduce pulse delay distortions, etc., have been solved. The advances made in improving fiber systems and the discovery of the sensitivity of the lightwaves propagating in fibers to

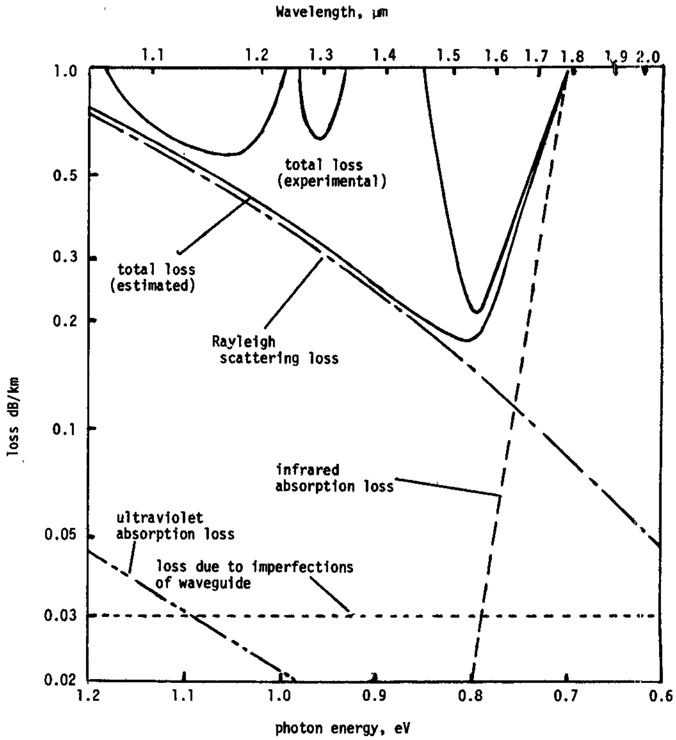

Fig. 1. Transmission-loss mechanism in the optical fiber (taken from [7]).

environmental changes, such as rotation of the fiber loop, the magnetic field, the pressure, the temperature, etc., have further opened up a new field of fiber applications, namely fiber sensors [12]. The net result is a very rapid increase in commercial and military applications of optical fibers that have not only led to practical applications, such as intracity and long-distance telecommunications, but also to a new impetus to search for methods to provide gigahertz bandwidths in optical-fiber communications. This renewed interest in large microwave bandwidths has, in turn, set the stage for research and development in single-mode fibers, in switching and signal processing in optical waveguides, in modulation techniques that will be able to generate very short pulses, and in high-speed coherent detection techniques.

In the meantime, the concept of using optical dielectric waveguides and devices fabricated on optical waveguides for switching, filtering, modulation, multiplexing, and signal processing were advanced in the late 1960's, while the term "integrated optics" was coined at that time [13], [14]. The idea of integrated optics was generated, in part, from extending directly the various microwave concepts into the optical wavelength and, in part, from applying semiconductor materials and processing technology to the fabrication of optical devices. Like microwave technology, it is essentially a single-mode technology. The goals of integrated optics are to provide effective modulation, switching, multiplexing, and many other signal processing functions on a single chip in order to obtain high-speed operations, to interface conveniently optical and electronic components, and to take advantage of batch fabrication methods. Success in the efficient excitation of guided waves by prism and grating couplers [15] and device demonstrations, such as the electrooptical modulation, acoustooptical switching, and filtering in the early 1970's, coupled with the rapid advances made in optical fibers, created visions of microwave-like complex optical circuits on waveguides interconnected by single-mode fibers for communications applications. However, extensive research in materials and processing technology is necessary in order to realize various components. For example, a GaAs diode laser interconnected with an optical waveguide on the same substrate requires different materials composition to be grown on the same chip so that the laser radiation will not be heavily absorbed by the waveguide. Research on the design of guided-wave devices that will circumvent the materials and fabrication limitations were also necessary. Examples of successful designs include the alternating $\Delta\beta$ modulator [16], the geodesic lenses [17], the Bragg electrooptical modulation [18], etc. Integrated and guided-wave optics, so far, remains primarily an area of research. In order to meet the needs of sources and receivers for fiber communications, research in semiconductor lasers and detectors and the materials technology for these devices constitutes a major area of research in guided-wave optics [19]. For example, the development of the MOCVD [20] and the MBE [21] processes for making semiconductor lasers has substantially improved laser performance. The research on GaInAsP and GaInAs lasers has yielded sources and detectors at the 1.3-μm and the 1.5-μm wavelength range. On the other hand, the demonstrated device performance has also created new interests in carrying out high-speed signal processing in optical waveguides. Signal processing in optical waveguides has two advantages. In comparison with electronic signal processes, it has the advantage of high-speed operation because of the short propagation delay and the parallel processing capability in a one-dimensional array of channels. In comparison with bulk optical signal processing, it has the advantage of the availability of planar microfabrication technologies that could be used to produce high-speed devices operating at low voltages and more complex optical circuits. Current examples of optical signal processors include the high-speed A/D converter [22], the integrated optical spectrum analyzer [23], and the various multiplexers and multipliers.

It is interesting to note that, in the early 1980's, due to the success of multimode fiber optical communications and the success in infrared laser and detector research, there is an even more extensive interest in single-mode fiber optical communications with gigahertz bandwidth, especially for long-distance high data rate systems at the 1.3- and 1.5-μm-wavelength range. This strong interest now gives new impetus to integrated and guided-wave optics research, since the single-mode guided-wave technology is well matched to the single-mode fiber technology. The needs for high-speed operations of computers and other signal-processing systems have also triggered a renewed interest in optical signal processing. If we try to make a list of the important advances made in fiber and integrated optics in 1982–1983, we may come up with the following list:

a) widespread introduction of local-area optical-fiber network into the commercial market by manufacturers;
b) installation of additional optical-fiber systems, including transocean undersea systems;
c) high-data rate and very long-distance single-mode optical-fiber communication at 1.3- and 1.5-μm wavelengths;
d) fiber-optical sensors;
e) semiconductor laser sources and *III–V* compound materials technology;
f) picosecond pulse generation;
g) microwave modulation and switching;
h) quantum well structures and optical bistable devices;
i) guided-wave signal processing;
j) integration of optical and microwave devices.

Clearly, a new generation of technology, the LIGHTWAVE TECHNOLOGY, has been born.

If we examine closely the operational techniques and the principles of the devices and systems used in lightwave technology (for example, the guided modes, the directional coupler, the traveling-wave modulators, etc.), they resemble closely those components used in microwaves. The primary difference between an optical and a microwave waveguide component is in the materials and microfabrication technology. Many of the researchers in lightwave technology were formerly researchers in microwaves. More importantly, the interconnection between microwaves and lightwave technology is becoming closer as we move into high-speed, high data rate communications and signal processing. For example, the design of the electrodes used in electrooptical modulation as microwave circuits are essential to the success of switching and modulation at the gigahertz frequencies. Potential integration of optical devices, such as lasers or detectors, with microwave devices on the same chip provide a tremendous advantage over purely optical or electronic signal-processing methods. We are already considering the use of optoelectronic methods to solve some of the signal-processing problems in computing and in VHSIC. Microwave components, such as the phased array, may also benefit from the use of injected laser signals transmitted through fibers to lock and to synchronize the phase of the elements in the array. In short, although there seems to be a branching off of the lightwave technology from the microwave in the 1970's, we can look forward to a merging of the two technologies in the 1980's.

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