Research Toward Optical-Fiber Transmission Systems
Part I: The Transmission Medium

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Part II: Devices and Systems Considerations

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Invited Paper

Abstract—The fundementals of optical fiber transmission systems including the fiber transmission medium, sources suitable for use as a carrier, modulation and detection techniques, and some system design considerations are reviewed.

The advent of low-loss optical fibers brings new dimensions to optical communication prospects. Fibers may soon be used much as wire pairs of coaxial cable are now used in communication systems. Transmission losses as low as 2 dB/km have been achieved. Experimental repeaters for fiber systems with 10^{-9} error rate at about 300-Mb/s pulse rate have been reported.

Fiber cabling and splicing are among the problems requiring new ideas in order to make feasible an operable system.

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This invited paper is one of a series planned on topics of general interest—The Editor.

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I. Introduction

OPTICAL-FIBER transmission systems will find application in the communications industry. The question is *when* will this occur, not *whether* it will occur. Whereas the idea of using light for the transmission of information dates back at least to the 1870's [1], it was not until the invention of the laser that a major research effort appeared warranted [2]. There followed several years of exploration of materials and laser structures, modulation and detection fundamentals, and techniques of guidance. The prospect appeared bright for systems carrying very large volumes of communications, but the anticipated date when very large systems would be needed appeared to be after 1980 [3], [4].

The advent of low-loss optical fibers added new dimensions to optical communication prospects. No longer is it necessary to have a large number of customers on a single transmission path in order to reduce the cost of the transmission medium to an attractive per-channel value. Fibers may soon be used much as we now use wire pairs or coaxial cables and may be applied to existing communications needs. Moreover, the complexity of the optical apparatus associated with multichannel multicarrier systems, such as would be needed on high-capacity lens-guided systems, is largely eliminated in fiber systems.

Fiber system advantages will be developed more fully later in this paper. The remarks here serve as introductory background for the choice of material in the body of the paper, and serve also to alert the reader to the fact that the prospects for optical communication systems are much more immediate and pervasive than previously viewed.

A brief historical note may be interesting to those new to the field. The first communications expert to direct serious attention to glass fibers for long-distance communications was Kao, then at Standard Telecommunications Laboratories in England [5]. At that time, 1968, typical fiber losses were above 1000 dB/km, but Kao suggested that purer materials should permit much lower losses. There followed a British Post Office sponsored effort to purify glass and to explore fiber transmission problems, both in industry and in the British universities as well as in the Post Office research laboratory. Interest in fibers soon became serious elsewhere—in the United States at Bell Laboratories and at Corning Glass Works, in Japan at Nippon Electric Company and at Nippon Sheet Glass Company, and in Germany at AEG-Telefunken and at Siemens and Halske. The breakthrough came in 1970 when Kapron, Keck, and Maurer of Corning Glass Works announced the achievement of losses under 20 dB/km in single-mode fibers hundreds of meters long [6]. Thereafter, progress in the science and technology of fiber transmission has developed along a broad front and continues vigorously now—as will be apparent in the following pages.

Section II treats the transmission properties of fiber waveguides. The various types of single-mode or multimode fibers are described, a description is given for the fields, and a review of new analytical techniques is presented. Descriptions of modes as well as ray-optic approaches are given. The mechanisms responsible for loss and dispersion are reviewed, and the techniques available for reducing dispersion are outlined. After a brief indication of the techniques for measuring loss and dispersion, the state of the art for the various fiber types is presented.

Section III discusses sources or carrier generators suitable for use in fiber transmission systems. The types of sources, the choice of carrier wavelength, the spectral width of their outputs, their brightness, their modulation capabilities, and their efficiencies are reviewed.

Section IV discusses modulation techniques and indicates their relation to fiber systems and to the particular carrier source. Direct modulation of the sources is considered in some detail and various optical modulators suitable for fiber systems are reviewed.

Section V contains a discussion of detectors in relation to fiber systems, with references to recent review papers.

Section VI gives an indication of the relation between the work on integrated optics and fiber transmission systems.

Section VII discusses some systems design considerations. The effects of modulation format, noise, and dispersion on system signal-to-noise ratio (or error rate) and repeater spacing are discussed, and the factors affecting choice of fiber design are reviewed.

Section VIII lists the advantages and disadvantages of fiber transmission systems and gives the general form of potential applications.

The paper is divided into two parts: Part I: The Transmission Medium, contains Section II; Part II: Devices and Systems Considerations, contains Sections III through VIII.

Part I: The Transmission Medium

II. Transmission Properties of Fiber Waveguides

A. Types of Fiber

In Fig. 1 we show the cross sections of important fiber types, and above each cross section we present a typical profile of the index of refraction for that fiber. A few typical dimensions are also shown to provide a physical feel for the scale.

The simplest fiber is the single-dielectric or unclad fiber shown in Fig. 1(a). A discontinuous change in index of refraction occurs at the fiber surface, from the dielectric's value n_1