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E.-G. Neumann

Single-Mode Fibers

Fundamentals

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Preface

Single-mode fibers are the most advanced means of transmitting information, since they provide extremely low attenuation and very high bandwidths. At present, long distance communication by single-mode fibers is cheaper than by conventional copper cables, and in the future single-mode fibers will also be used in the subscriber loop. Since single-mode fibers have many applications, a variety of people need to understand this modern transmission medium. However, waveguiding in single-mode fibers is much more difficult to understand than waveguiding in copper lines.

A single-mode fiber is a dielectric waveguide operated at optical wavelengths. Since 1961, I have been involved in experimental and theoretical research on dielectric rod waveguides in the microwave region. From the experiments, I learned much about the properties of a wave guided by a dielectric rod or a glass fiber, especially about its behavior at waveguide discontinuities like bends, gaps, or the waveguide end. Since 1972, my co-workers and I have also been investigating dielectric waveguides at optical frequencies, and since 1973 I have lectured on "Optical Communications". These activities have shown that there is a need for a tutorial introduction to the new technical field of single-mode fibers. In this book the physical fundamentals are emphasized and the mathematics is limited to the absolutely necessary subjects. Besides presenting a physical explanation of waveguiding in single-mode fibers, it is also the aim of this book to give an overview of the knowledge accumulated in this field. Many references are given in the text to the original papers in technical journals or conference proceedings.

E.-G. Neumann

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Contents

1. Introduction

1.1 Historical Note

Single-mode fibers are dielectric waveguides for optical waves. Although dielectric waveguides have a history that goes back as far as 1910 [Hondros and Debye 1910], they have never been used for long distance communication at microwave frequencies because of the losses in the dielectric materials available.

Then, in 1966, Kao and Hockham [1966] proposed to use glass fibers as dielectric waveguides at optical frequencies for long distance communications. At that time, the attenuation of the best optical glasses available was of the order of 1000 dB/km. However, mainly by purifying the materials, it has been possible to reduce the losses by several orders of magnitude: In 1972, fibers with an attenuation below 20 dB/km were reported [Kapron et al. 1970a,b]. At present, fibers with an attenuation as low as 0.2 dB/km are commercially available, and a large number of lightwave communication systems are in use.

Because of the availability of semiconductor light sources and silicon photodetectors and the difficulties of jointing single-mode fibers, the first generation of optical communication systems used multimode graded-index fibers at wavelengths of about 0.85 μm. For repeater distances of typically 10 km, they could transmit a binary signal with a maximum bit rate of about 100 Mb/s.

Since the signal attenuation decreases with wavelength, it is advantageous to use longer wavelengths [Kimura and Daikoku 1977]. Therefore, in the second generation of fiber optic systems, the wavelength was shifted to 1.3 μm, but multimode graded index fibers were still being used. Because of the smaller attenuation of about 0.4 dB/km, link lengths of up to 50 km were possible; however, because of the spread in time delay for the several hundred modes propagating in multimode fibers, the maximum bit rate was of the order of 100 Mb/s.

The third generation of fiber optic systems offered higher transmission capacities by using single-mode fibers, while continuing to operate in the 1.3 μm band. Third generation systems operating at data rates of 565 Mb/s are presently being installed.

The loss minimum for silica fibers is at a wavelength of 1.55 μm. The lowest attenutation ever reported is 0.154 dB/km at 1.55 μm [Kanamori et al. 1986]. Practical cables can have losses of 0.2 dB/km. Because of this low loss, the fourth generation, which is still in its research and development stage, will use single-mode fibers at this long wavelength, thus allowing repeater spacings of more than 100 km and bit rates of more than 1 Gb/s [Lilly and Walker 1984].

Additional future generations of optical communication systems will use coherent optical carriers and heterodyne receivers, or fibers made of new low-loss materials like heavy-metal fluoride glasses instead of silica glass.

In 1983, the first single-mode system has been introduced into commercial use and it is to be expected that, in the future, single-mode fibers will dominate in long distance communication. Presumably, single-mode fibers will be used also for shorter links, e.g. in local area networks (LAN's) [Rocher 1985; Cochrane et al. 1986] or subscriber loops [Kaiser 1985; Krumpholz 1985a; Krumpholz 1985b; Kaiser 1986]. First, these systems will operate with cheap LED-emitters [de Bortoli and Moncalvo 1986], but later, the transmission capacity can easily be upgraded by replacing the LED's with semiconductor lasers. Far in the future, further upgrading may be accomplished by introducing heterodyne receivers and frequency division multiplexing [Kaiser 1985; Khoe and Dieleman 1985; 1986].

The history of fiber-optic communications, in general, has been reviewed several times [Miller S.E. and Tillotson 1966; Kapany 1967; Miller et al. 1973a: Miller et al. 1973b; Clarricoats 1976; Börner 1980; Li 1983; Suematsu 1983; Kapron 1984a; Niizeki 1984; Kapron 1985; Henry 1985].

In contrast to this, the history of single-mode fibers has been described only a few times [Hooper et al. 1985; Seikai et al. 1985; Hooper 1986]. Optical dielectric-waveguide modes in glass fibers were first analyzed [Snitzer and Hicks 1959; Snitzer 1961] and observed experimentally [Osterberg et al. 1959; Snitzer and Osterberg 1961] in 1959. When research on optical fiber communication started in 1966, the main interest was in single-mode fibers [Kao and Hockham 1966; Krumpholz 1970; Kao et al. 1970; Börner 1971; Krumpholz 1971]. However, because of the difficulties of launching and jointing, at the beginning of the 1970's, the interest shifted away from single-mode fibers to multimode fibers. However, at the end of the 1970's, it became obvious that the bandwidth of long graded-index multimode fibers is very limited, and single-mode fibers became very interesting again.

1.2 Multimode and Single-Mode Fibers

The relatively small bandwidth of multimode fibers is the main reason for the strong trend to introduce single-mode fibers with bandwidths that are wider by a factor of at least 100. With a view to the future, only single-mode fibers can be used when one wants to replace the present direct photo-receivers, which resemble the first crystal radio receivers of the 1920's, by more sensitive and frequency-selective heterodyne receivers. Moreover, most integrated optical components use single-mode dielectric channel waveguides, so that only single-mode fibers can be coupled effectively to integrated optical repeaters.

Other advantages of single-mode fibers over multimode fibers are that they have lower fiber attenuation, lower splice and connector loss, larger production tolerances, lower cost, they preserve coherence and the degree of polarization, and exhibit useful nonlinear effects [Kapron 1984a]. In multimode fibers, attenuation and pulse broadening depend on the launch conditions, which makes these quantities difficult to define, to measure, and to calculate in advance. In contrast, in single-mode fibers, the propagation characteristics are independent of the launch conditions. The properties of single-mode fibers for long distance telecommunications have been compared with those of multimode fibers by Gambling and Matsumara [1979].

It has been argued in the past that it would be difficult to couple light into the tiny core of a single-mode fiber and that the losses at connectors and splices would be very high. However, in the factory one can nowadays couple a semiconductor laser to a short section of single-mode fiber, a so called pigtail, with a loss of about 3 dB. The pigtail can easily be fusion-spliced to the system fiber with an insertion loss of the order of only 0.1 dB. Today, single-mode fiber connectors with losses of less than 1 dB are also commercially available.

Because of the advantages of single-mode fibers, many optical and electrical engineers and technicians, as well as managers, in industry and in telecommunication administration, will have to study the principles and applications of single-mode fibers. Even those engineers who know multimode fibers will find that some concepts cannot be transfered to the new technology. For instance, it is easy to understand how light waves are guided by a multimode fiber: in step-index fibers by multiple total reflection of the rays at the core-cladding interface, and in graded index fibers by continuous ray bending. To understand waveguiding by single-mode fibers is far more difficult.

Because of the tiny core of single-mode fibers, the methods of geometrical optics [Cornbleet 1983] fail to describe the wave properties adequately. One has to use the more accurate and more complicated methods of wave optics for analyzing single-mode fibers. The concept of light rays of "zero" diameter cannot be applied. One has to consider light beams of finite diameter, which have a natural tendency to increase their width. Thus, diffraction effects have to be taken into account. Therefore, the ray path approach used with multimode fibers is no longer applicable, and electromagnetic field theory must be used.

Of course, most of the many textbooks on optical communications [Kapany 1967; Kapany and Burke 1972; Marcuse 1974; Arnaud 1976; Unger 1977a; Miller S.E. and Chynoweth 1979; CSELT 1980; Adams 1981; Barnoski 1981, Grau 1981; Marcuse 1981a; Sharma A.B. et al. 1981; Marcuse 1982a; Okoshi 1982; Kersten 1983; Snyder and Love 1983; Cancellieri and Ravalioli 1984; Unger 1984, Unger 1985; Geckeler 1986a] also report on the wave theory of fibers, from which one can deduce information on wave propagation in single-mode fibers. However, the complexity of the theory even for the simple step-index profile makes it difficult to extract general rules for the properties of single-mode fibers. Special properties of single-mode fibers are described in more than 4000 original publications in the literature. Since these papers are scattered over about 20 technical journals, it may be difficult to locate a paper covering a special problem.