1

INTRODUCTION TO WDM

1.1 WDM THEORY

Wavelength division multiplexing (WDM) refers to a multiplexing and transmission scheme in optical telecommunications fibers where different wavelengths, typically emitted by several lasers, are modulated independently (i.e., they carry independent information from the transmitters to the receivers). These wavelengths are then multiplexed in the transmitter by means of passive WDM filters, and likewise they are separated or demultiplexed in the receiver by means of the same filters or coherent detection that usually involves a tunable local oscillator (laser).

WDM is an efficient means for increasing the transport capacity, or usable bandwidth, particularly of optical single-mode fibers. It also allows the separation of different customers' traffic in the wavelength (or optical frequency) domain and as such can be used as a multiple-access mechanism. The respective scheme is called wavelength-division multiple access (WDMA).

Modulated and multiplexed signals must be separated from each other or demultiplexed in order to be demodulated (otherwise, cross talk may appear). For separation, each pair of the respective signals must support orthogonality. For any two signals to be orthogonal, their scalar product must be zero:

$$(\underline{f},\ \underline{g}^*) = \underline{f}^{\mathrm{T}} \cdot\ \underline{g}^* = \sum_i f_i \cdot g_i^* \stackrel{!}{=} 0, \quad \text{with} \quad f_i \cdot g_i^* = \int_a^b f_i(x) \cdot g_i^*(x)\mathrm{d}x,\ \ i = 1, \cdots, N. \tag{1.1}$$

Wavelength Division Multiplexing: A Practical Engineering Guide, First Edition.
Klaus Grobe and Michael Eiselt.

(f, g^*) is the scalar product of complex functions, where * denotes complex conjugation. Equation (1.1) is also written for vector functions in order to be able to consider effects of orthogonally polarized signals.

The vanishing scalar product of the two signals is equivalent to a vanishing cross-correlation product or cross-correlation function (CCF). For the CCF, meaningful integration bounds must be considered, for example, integration over one symbol period. For optical WDM, the requirement (1.1) is easily fulfilled. Given that the different wavelength channels, including the Fourier transform-induced broadening due to the modulation, are properly spaced in the wavelength domain, any two different passbands of the WDM multiplexing (MUX) and demultiplexing (DMX) filters are orthogonal with respect to each other. In reality, Eq. (1.1) may not be achieved exactly, but only approximately due to linear or nonlinear cross talk.

WDM is the generalization of frequency-domain multiplexing that is long known from radio and coaxial transmissions. With a WDM channel, it can be combined with any other of the known electrical multiplexing or multiple-access schemes. These include electrical frequency-domain multiplexing, which is then referred to as subcarrier multiplexing (SCM), time-domain multiplexing (TDM), and code-domain multiplexing. One scheme of particular interest for both the multiplexing and multiple access is orthogonal frequency-domain multiplexing (OFDM), which can be applied within a wavelength channel or covering the optical frequencies of several wavelength channels. The respective multiple access schemes are time-domain multiple access (TDMA), subcarrier multiple access (SCMA), frequency-domain multiple access (FDMA), and code-domain multiple access (CDMA).

1.2 HISTORY OF WDM

The development toward commercial WDM transport systems as the common basis of all metropolitan area, regional, national, and international telecommunications networks was enabled by a number of relevant milestones:

- 1960: first laser developed [1]
- 1966: first description of dielectric waveguides as a potential means for data transmission by Kao and Hockham [2]
- 1970: first low-loss optical fiber produced (~20 dB/km) [3,4]
- 1976: first InGaAsP diode laser for 1300 nm window produced [5]
- 1978: first low-loss single-mode fiber produced (~0.2 dB/km) [6]
- 1978: first experimental WDM systems developed [7]
- 1987: first Erbium-doped fiber amplifier (EDFA) developed [8,9]
- 1995: first commercial WDM systems available

These milestones were accompanied by the development of ever-improved components (e.g., diode lasers for the 1550 nm window) and various types of single-mode fibers.

High-speed single-mode fiber transmission started in 1981 with single-channel transmission at ∼1300 nm. Reasons were the availability of suitable semiconductor diode lasers and the fact that the first single-mode fibers [which are meanwhile referred to as standard single-mode fibers (SSMF)] had their region of lowest chromatic dispersion (CD) around 1300 nm. CD was the strongest deteriorating effect for early fiber transmission, limiting maximum reach. In addition, the region around 1300 nm had lowest fiber attenuation for wavelengths lower than the water-peak absorption region. The next step—for single-channel transmission—was to align the regions of lowest CD and lowest fiber attenuation in order to further maximize reach, in particular for the upcoming 10 Gb/s transmission. Since fiber attenuation is basically a material characteristic that cannot be influenced significantly for silica fibers, the region of lowest CD had to be shifted to ∼1550 nm in order to align both parameters. CD can be shifted since it depends on both the material and waveguide (geometry) characteristics. Hence, it can be shifted by designing a suitable radial refractive index profile. This has been done around 1990, and the result is the so-called dispersion-shifted fiber (DSF)—sometimes also referred to as dispersion-shifted single-mode (DSSM) fiber. DSF was heavily deployed in Japan and certain other regions (e.g., parts of the United States and Spain).

The deployment of DSF badly interfered with the usage of first WDM systems. The problem was caused by transmitting several WDM channels around 1550 nm, at close-to-zero CD. The EDFA, which had meanwhile been invented and which revolutionized long-reach fiber transmission, enabled long transparent link lengths exceeding 600 km. With increasing transparent link lengths and increasing total and per-channel fiber launch power, a fiber characteristic—nonlinearity—got relevant that had not been considered seriously before. Though basic work on fiber nonlinearity had been published in the 1970s (see Section 2.2), one of the nonlinear effects, four-wave mixing (FWM), now started to seriously limit WDM transmission on real-world fibers. FWM is the parametric mixing effect that occurs due to the fundamental fiber's cubic Kerr nonlinearity. As with all parametric mixing, it relies on phase matching between the mixing waves that can be achieved in real fiber in the *absence* of CD. This was just the design goal for single-channel transmission DSFs. Once it efficiently occurs, FWM cannot be counteracted anymore; it thus fundamentally limits reach.

The problem with WDM transmission on fibers with close-to-zero CD then led to the development of a family of modified single-mode fibers. These fiber designs, known as nonzero dispersion-shifted fibers (NZ-DSF) or dispersion-flattened single-mode (DFSM) fibers, followed the idea to provide nonzero CD that is yet smaller than that in SSMF in order to reduce both the linear and nonlinear distortions. The second-generation WDM systems could achieve approximately the same maximum reach (which was still limited in the 600 km range) on SSMF and NZ-DSF. With transparent reach extended into the ultralong-haul domain and the techniques for optical CD compensation having been developed during the 1990s, it turned out that nonlinear distortions were still the dominating reach limitation. This led to the development of several NZ-DSF with increased (and also flattened) CD. Finally,

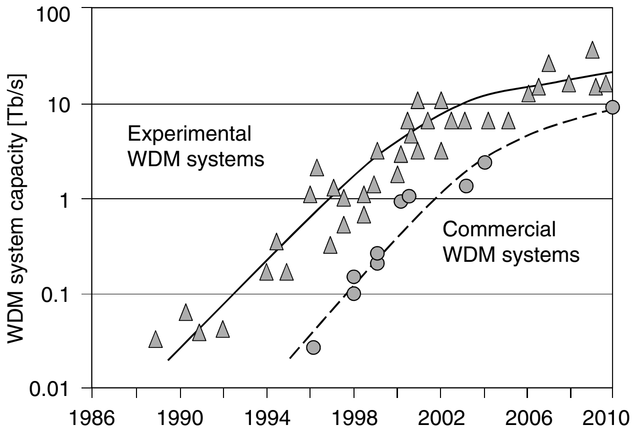

FIGURE 1.1 Development of WDM systems transport capacity over time.

with the product of transparent reach and total capacity (in terms of number of WDM channels and per-channel bit rate) further increasing, it turned out that in the presence of nonlinearity, SSMF with their high CD are the optimum choice of silica fibers. Further improvements of the bandwidth-reach product will likely require disruptive new fiber types.

Driven by improvements of components and modulation and equalization techniques, the total transport capacity of WDM systems has largely increased since the first experiments with WDM. This is shown in Fig. 1.1 for both the experimental and commercial WDM systems.

Two aspects can be derived from Fig. 1.1. First, commercial WDM systems are following "hero" experiments somewhat more timely now and both are approaching an area of slowed down capacity improvement. Over the next few years, WDM on SSMF will finally reach what is now known as the nonlinear Shannon limit [10]. Further progress beyond this limit will require new fiber types.

REFERENCES

1. T.H. Maiman, Stimulated optical radiation in ruby, Nature, Vol. 187, No. 4736, 1960, pp. 493–494.
2. K.C. Kao and G.A. Hockham, Dielectric-fibre surface waveguide for optical frequencies, Proc. IEEE, Vol. 113, No. 7, 1966, pp. 1151ff.
3. D.B. Keck et al., On the ultimate lower limit of attenuation in glass optical waveguides, Appl. Phys. Lett., Vol. 22, No. 7, April 1973, pp. 307ff.
4. P.C. Schultz Making the first low loss optical fibers for communications, ECOC2010 Torino, September 2010.
5. J. Hsieh et al., Room-temperature cw operation of GaInAsP/InP double-heterostructure diode lasers emitting at 1.1 μm, Appl. Phys. Lett., Vol. 28, No. 12, 1976, pp. 709–711.

6. H. Murata and N. Inagaki, Low-loss single-mode fiber development and splicing research in Japan, IEEE J. Quantum Electron. Vol. 17, No. 6, June 1981, pp. 835–849.
7. W.J. Tomlinson and C. Lin, Optical wavelength-division multiplexer for the 1–1.4-micron spectral region, Electron. Lett., Vol. 14, May 1978, pp. 345–347.
8. R.J. Mears et al., Low-threshold tunable CW and Q-switched fiber laser operating at 1.55 μm, Electron. Lett., 22, 1986, pp. 159–160.
9. R.J. Mears et al., Low-noise erbium-doped fiber amplifier at 1.54 μm, Electron. Lett., Vol. 23, 1987, pp. 1026–1028.
10. R.-J. Essiambre et al., Capacity limits of optical fiber networks, IEEE J. Lightwave Technol., Vol. 28, No. 4, 2010, pp. 662–701.