Review scientific paper

Informacije MIDEM
Journal of Microelectronics, Electronic Components and Materials
Vol. 44, No. 3 (2014), 177 – 184

Research challenges in optical communications towards 2020 and beyond

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Abstract: This paper presents an overview of future research activities in the field of optical telecommunications. The year 2020 is considered a milestone, when the capacity of optical communication links via a single optical fiber will reach the physical limitation called the "fiber wall". It is expected that advances in systems with a standard, single-mode, optical fiber, which enables increasingly higher transmission capacities due to accelerated scientific research, will reach the point where the capacity of the optical link via a single optical fiber will no longer grow. Due to this collision with the "fiber wall", research efforts to develop future solutions are all the more necessary. This article provides an overview of the fields in which the future development of optical communications will give the most focus. In the field of optical devices and components, the development goes in the direction of integrated optics and new optical fibers. In order to achieve the objectives, the new communication techniques comprise coherent communications, multidimensional modulation formats and multiplexing techniques, as well as the use of digital signal processing. Modern optical networks extend from the high-performance fiber optic connections in the backbone to broadband access in user's home, in the future their architecture will enable an adaptability to wavelength, bandwidth and modulation format. The main aim of the development towards 2020 and beyond is to build optical communication systems that will enable the transfer of large amounts of data with the minimum power consumption using the simplest and cheapest equipment.

Keywords: optical devices, optical fiber, optical networks, optical communication

Raziskovalni izzivi optičnih komunikacij do in preko leta 2020

Izvleček: Članek predstavlja pregled bodočih raziskovalnih aktivnosti na področju optičnih telekomunikacij. Leto 2020 se pojmuje kot mejnik, ko bo predvidoma zmogljivost optične komunikacijske zveze po enem optičnem vlaknu dosegla fizično omejitev imenovano »vlakenski zid«. Pričakuje se da bodo raziskave v sistemih s standardnim enorodovnim optičnim vlaknom, pri katerih se poskuša doseči vedno višje prenosne zmogljivosti, prišle do položaja, ko zmogljivost optične zveze po enem optičnem vlaknu ne bo več napredovala. Zaradi trčenja v »vlakenski zid«, so raziskovalni napori v bodoče rešitve toliko bolj potrebni. V članku je narejen pregled področij na kareta se bo razvoj optičnih komunikacij najbolj osredotočil. Na področju optičnih naprav in elementov gre razvoj v smeri integrirane optike in razvoja novih optičnih vlaken. Z namenom doseganja svojih ciljev nove komunikacijske tehnike vključujejo koherentne komunikacije, večdimenzionalne modulacijske formate in tehnike multipleksiranja ter s pridom uporabljajo digitalno obdelavo signalov. Sodobna optična omrežja se raztezajo od visoko zmogljivih optičnih povezav v hrbtenici do širokopasovnega dostopa v uporabnikovem domu. Njihova arhitektura pa bo v bodoče omogočala prilagodljivost na valovno dolžino, pasovno širino in modulacijski format. Cilj razvoja do in preko leta 2020 je izdelati optične komunikacijske sisteme, ki bodo omogočili prenos velike količine podatkov z najmanjšo porabo moči s pomočjo najenostavnejše in najcenejše opreme.

Ključne besede: optične naprave, optično vlakno, optična omrežja, optične komunikacije

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1 Introduction

Optical communications have been continuously developing over the past four decades and today they represent a mature industry [1]. New applications and services that require more and more data, and users who expect the instant and correct delivery of such data, without having to wait and experiencing errors, require increasingly sophisticated optical communication systems. Users are mainly interested in the speed and the quality of the services, which provide them with a good user experience [2]. In this context, it is necessary to bear in mind that underneath a user's requirements there are many communication levels. Operators of telecommunications networks should ensure the smooth operation of their systems, which face the challenges of a constant increase in data traffic that must be transferred as fast as possible and with the least possible delay. They are, however, constrained by the costs associated with building (capital expenditures – Capex) and operating (operational expenditure – Opex) a telecommunications network. From the upcoming systems telecommunications operators expect a better ratio between transmission capacity and costs.

The capacity of the optical communication link is subject to the equipment available and its electronics, the communications channel and the type of transmission signal. All three elements are equally important for the correct and immediate delivery of telecommunications data, and therefore future researches will also be focused on these main areas: new optical devices, improved communication techniques and new architectures for optical networks (as shown in Figure 1). It is in these areas of optical communications that the most innovative solutions and development achievements can be expected in the future. There are many studies based on new modulation methods and new models for data transmission, which can also handle non-linear and randomly changing optical communication channels, whereby the objective is to provide higher bit rates and better signal or service quality. For these reasons, research in the field of signal issues, questions related to the transmission channel and electronics in the receiver and transmitter are closely inter-related and interdependent.

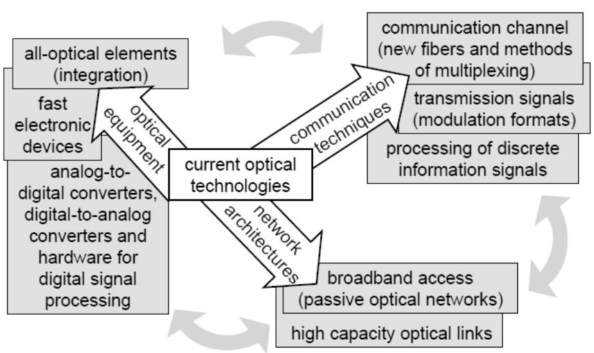

Figure 1: Three directions of development in optical communications.

Ever more powerful optical links, which are able to transmit more and more data over increasing distances, are the results of previous research. These optical links are now adapted to the use of a standard, single-mode, optical fiber, which has been a well-established transmission medium for a long time [1]. If future research achievements with the same time increment will shift the capacity boundaries of optical communication links by single-mode optical fiber [3], it is expected that by around 2020 the physical limit will be reached when the capacity of an optical line via a single optical fiber will no longer progress. The exact time of the emergence of the point of capacity constraint for a single mode fiber, called the "fiber wall" is difficult to predict. At present, research is needed, which will focus on new solutions in the field of optical backbone networks [4]. Once the "fiber wall" is achieved, it will be too late for this kind of research, because service providers will not be able to afford the subsequent installation of a parallel network in order to increase capacity. The installation of a parallel network is linked to Capex and Opex, which increase almost linearly with increasing capacity.

2 Optical devices

In the field of optical communication devices, developments are in the direction of integrated optics known as Planar Lightwave Circuits (PLCs) or Photonic Integrated Circuits (PICs). Integration has become an important tool in the effort to reduce the production costs of optical devices, increase the functionality of telecommunications networks and, ultimately, limiting the impact on the environment in relation to the amount of carbon-footprint emissions resulting from the use of electricity.

The development of optical circuits suggests that cheaper monolithic solutions will replace the current hybrid solutions [5]. The current technology of hybrid integrated circuits in a single enclosure combines various integrated circuits or discrete components that, connected together, perform certain optical and electrical functions. Future, monolithic integrated circuits will be a combination of passive and active circuit elements in a single optical chip. The aim of modern research is the integration of light sources (lasers), transmitters, modulators and signal processing elements (and vice versa; detectors, demodulators and receivers) on a single semiconductor substrate. Special attention will continue to be given to optical receivers as, based on the entire telecommunications connection, the signals in the receiver are the weakest and therefore this requires careful treatment.

The developments in the field of optical devices also includes the now familiar Micro-Electro-Mechanical Systems (MEMS) [6], Free-Space Optics (FSO), discrete optics, photonic crystals, ring resonators, gratings and plasmonic circuits and devices.

In relation to the development of new devices, the research will not focus only on III-V semiconductors (such as indium phosphide - InP) [7] but also on devices based on silicon, which is the so-called area of Silicon Photonics [8], and its family of oxides and nitrides. Silicon is more abundant, cheaper and more effective than III-V semiconductors. The latest developments in the field of integration are the integration of silicon waveguides with silicon nitride waveguides, or organic materials, the integration of waveguides of lithium niobate (LiNbO3) with silicon waveguides and the integration of liquid crystals with silicon waveguides. In the future these and other integrations will also be an important part of research in the field of optical materials and technologies.

The fact is that optical integrated circuits are much more expensive than the existing electronic integrated circuits; therefore, for many years the signal processing has been transferred from the optical domain to the domain of electronics. Electronics is also much more effective than optics, because it uses Digital Signal Processing (DSP). In the past decade, DSP became much more effective than analogue signal processing, which is still in use when we are working in the optical domain. Because there are no new technologies on the horizon that would enable the cheaper processing of optical signals, integration will retain an important role in combining the fields of optics and electronics in the years to come. According to the new system requirements, it is expected that the new generation of optoelectronic devices and integrated optics will be adaptable to the wavelength, bandwidth and modulation format [9]. Future research will also focus on the development of entirely new all-optical devices, which will have less consumption than the current opto-electronic solutions.

3 Communication techniques

The aim of the further development of optical communications is thus to extend the reach as well as increase the transmission capacity of optical links. Currently, the use of coherent optical systems is very interesting and very important. This idea emerged in the early 1980s and then "disappeared" due to the invention of optical amplifiers [1]. Now, a new need for the use of coherent systems has emerged that can come to life in reality with the use of new optical devices. The great advantage offered by coherent systems is the possibility of performing electronic equalization of the optical channel. Coherent optical systems can operate at very low levels of the received signal and very high bit rates, which range into the sphere of Tbit/s [10]. Interestingly, coherent optics uses techniques that are commonly used in radio systems, such as multi-level modulation formats (Differential Phase Shift Keying (DPSK), Quadrature Phase Shift Keying (QPSK) and various forms of Quadrature Amplitude Modulation (QAM)) and techniques with more orthogonal carriers known as Orthogonal Frequency-Division Multiplexing (OFDM). In order to correctly work a coherent system has to measure the complete received electric field (amplitude, phase and polarization) and use this information to electronically equalize chromatic, polarization and even modal dispersion.

More than two decades ago Wavelength Division Multiplexing (WDM) technology began to enforce itself on the backbone optical networks. In all the previous years, an increase in the transmission capacity of WDM technology went in the direction of increasing the number of channels, the used bandwidth and bit rate for each channel and reducing the channel spacing. All four methods of development have now reached a high level of engineering perfection. Modern, spectrally efficient systems have a large number of channels (sometimes over a hundred), which extend beyond the Conventional (C), Long (L) and even Short (S) wavelength bands, wherein in each of the channels the traffic can run with a bit rate of 40 Gbit/s and more. In accordance with the ITU-T standardization the downward trend of channel spacing has led to the current use in the distribution network of 12.5 GHz. The new network elements are adapting to the flexible grid of the optical spectrum.

While increasing the spectral efficiency of WDM systems by reducing the spacing between individual WDM channels, the development goes in two largely equivalent directions. In this way, complex procedures for shaping the spectrum are used, based on the orthogonality between the different WDM channels, either in the time domain or in the frequency domain. As an alternative to coherent OFDM transmission the system is known as the Nyquist WDM (Ny-WDM). In the case of Ny-WDM, the subcarriers are spectrally shaped so that their bandwidth is close to, or equal to, the Nyquist border for the emergence of inter-symbol interference and crosstalk between the channels [11]. In this context, to separate closely spaced WDM channels, highly selective optical filters are no longer used; instead, advanced Digital Signal Processing (DSP) [12] and Digital-to-Analogue Converters (DAC) are employed, which enables the precise formulation of the spectrum for each channel [13].

The use of high bit rates and long fiber ranges by WDM technology and erbium-doped fiber amplifiers (EDFA) triggered some previously insignificant restrictive phenomena. Among them, it is necessary to draw attention to Polarization Mode Dispersion (PMD) and the nonlinearity of the optical fiber. The increased importance of PMD gave rise to many research studies, based on addressing the weaknesses and limitations as a result of the PDM as well as Chromatic Dispersion by means of digital signal processing. As shown in Figure 2, the transfer of the optical fiber, on the one hand limits the low signal-to-noise ratio, and on the other, a too high nonlinearity is becoming noticeable at large distances and high optical powers. The transfer can be improved by reducing the attenuation and non-linearity in an optical fiber, wherein Large-Aeff Pure-Silica Core Fiber (LA-PSCF) optical fibers are essential as they introduce the lowest attenuation (up to 0.161 dB/km) and two times smaller non-linearities known in a standard single-mode fiber.

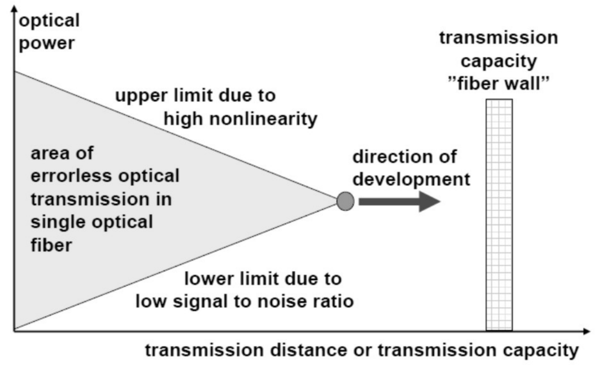

Figure 2: Transmission limits for optical fiber communications.

For radio communications the originally developed techniques are also used in the case where a so-called multimode fiber transmits a smaller number of modes, which forms the optical Multiple-Input Multiple-Output (MIMO) system [14]. As shown in Figure 3, while in radio communications the MIMO is reached with a larger number of transmission and reception antennas, in optical communications, multipath in multi-mode optical fiber is utilized. The generic dispersion in the fiber acts as a multipath in the space.

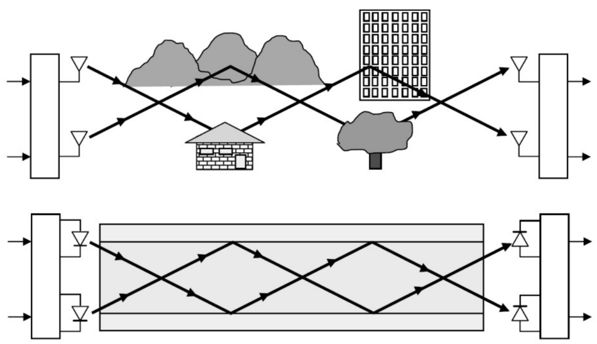

Figure 3: Radio and optical multipath.

In addition to the established multiplexing techniques, which can increase transmission capacities at the expense of the multi-dimensionality of the frequency, space or polarization, in recent years the exploitation of Orbital Angular Momentum (OAM) of electromagnetic waves presents itself as a new dimension of multiplexing in optical communications. In this context the orthogonality of the so-called vortex modes or modes with a phase singularity are exploited, which carry different orbital angular momentum [15]. Some researchers do not consider the use of OAM as a new technique of multiplexing, but as spatial multiplexing, which includes the MIMO. The similarity between optical MIMO and OAM is, in optical communications, seen in the fact that both of them exploit more modes for data transmission. They differ in the way of distributing the data between modes. The main difference between radio MIMO and optical MIMO is noticeable in the way of reception or the design of the receiver. Radio MIMO techniques require digital signal processing at the receiver side, with which individual data streams are distinguished by a knowledge of the transmission channel characteristics. Before and during the communication, the characteristics of the transmission channel are determined by a learning sequence, which is known to the receiving side. Neither digital processing nor a knowledge of the channel are not required for multiplexing with OAM, because to distinguish between the signals only spatial filtering is needed with this technique. In the case of radio technology, the difference is all the more apparent than in optical communications, because in OAM a direct sight between the transmitter and the receiver is desired, in MIMO the key requirement is a strongly emphasized multipath and thus Rayleigh statistics of fading.

For the transmission of multiplexing using the OAM via the optical fiber, a single-mode fiber is fundamentally inappropriate, since it does not allow the enlargement of more than one mode. Potentially, the single-mode fiber could be used at shorter wavelengths, where it acts as a few-mode fiber, or it would be necessary to use a fiber with an appropriately larger core diameter. If vortex modes spread along the normal multi-mode fiber, they make undesired coupling due to the frequency degeneration and birefringence caused by the bends and technological irregularities in the fiber. The ability to manage the vortex modes can be improved by using new types of fibers. For example, a vortex fiber [16] solves the problem of degeneration and enables the management, especially, of the lower modes (Figure 4). The air-core fiber is currently seen as the best solution for the management of higher modes.

Figure 4: Single-mode fiber (SMF), multi-mode fiber (MMF), few-mode fiber (FMF), vortex fiber, hollow-core photonic band-gap fiber (HC-PBGF).

Transmission systems up to the point are based on single-mode (single-core) optical fiber, but current technology is approaching the limit of the capacity of single-mode fibers in the C and L bands. By approaching the theoretical capacity limits of optical fiber [17] in inter-metropolitan connections, we will soon witness the use of a technology that seemed impossible five years ago. The example of such technology is Space-Division Multiplexing (SDM) in multi-core fibers (Figure 5) [18], which is the most realistic step to Pbit/s links [19], which are located behind the "fiber wall". In the past few years we have been witnessing a 10x increase in capacity of optical transmission by using spatial multiplexing. The development of new multi-core fibers will further increase system performance. Future research projects will deal with merging few-core fibers with each other and with a single-core fiber and with the development of transmitters, receivers and amplifiers for few-core fiber connections. Finally, few-core systems will also require commutations between the cores and the individual channels and bit streams within the SDM system, which will also be the focus of future research efforts.

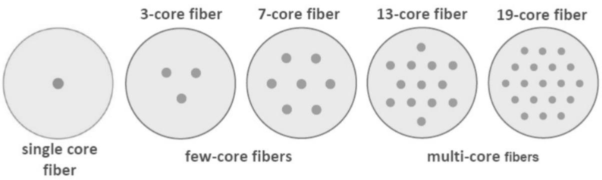

Figure 5: Single-core fiber (SCF), few-core fibers (FCF), multi-core fibers (MCF).

4 Optical networks

Research and development in the field of optical networks move towards mass broadband access in the vicinity of the end user and in the direction of high-performance optical connections between cities. The current three-segment network, comprising access, metropolitan and core networks, will in the future be substituted by a two-segment network that will include a combined metropolitan-access network and a core network.

Around the world, as well as in Slovenia, there is a lot of interest in managing the fiber all the way to user's home - Fiber to the Home (FTTH) [20]. A lot of development work has been invested in network architectures that enable high bit rates and the long reach of fiber from the central office to the user's home. In the background of new services there is the need for FTTH that will enable transmission speeds of up to several Gbit/s. The entire telecommunications sector also strives to meet the requirements for bandwidth in access networks for the required price of mass economy. For this purpose a number of new passive optical network architectures have been developed. For many years, Passive Optical Network (PON), based on the technology of classification using Time Division Multiplex (TDM), has been known. In the process of increasing the speed from 2.5 Gbit/s to 10 Gbit/s TDM-PON still benefits from technical improvements. The wavelength remodulation optical access network schemes are promising technique to reduce the crosstalk from downstream signal [21]. It should be noted that researches in the field of PON systems with a wavelength selectivity (WDM-PON) have been less frequent in last few years, as the requirement for building, or at least upgrading, the optical network presents operators with an unwelcome obstacle. TWDM-PON (Time Wavelength Division Multiplexing PON) and even coherent PON are becoming more noticeable.

Today, optical systems provide the backbone for the transmission of large amounts of data generated online, while using a packet, which is cheaper and more effective than any other type of transmission. The development is still in progress towards finding better and more expansive optical systems with high bandwidth, where the aim is to develop optical transmission systems that are suitable for the high-speed networking of continents, major cities and data centers. In this context, many researches focus on Software Defined Networks (SDN) [22], which will enable a transformation of the network without significant operator interference and in accordance with the demand for data transmission. SDN combine the optical network devices and the software that controls them. Programmable network interfaces enable a flexible optical network, which will have a new functionality such as dynamic control and virtualization. The optical physical level thereby obtains a certain degree of network intelligence, which will enable increased efficacy and the expansion of services. However, this also means more complexity in network operations, and therefore numerous studies in this area will be needed to optimize the algorithms of the design of optical networks [23] as well as the dynamic allocation of bandwidth [24]. Maybe this will allow the deletion of, or at least softening of, the boundaries between telecommunications operators and content providers, which demand greater flexibility.

A significant proportion of all the optical connections are now also used to connect the data centers and within high-performance computers, because the compactness and capacity of optical communication has become indispensable to the design of large data-handling systems [25].

Data-center networks form a powerful backbone infrastructure for many existing internet service providers as well as the emerging providers of cloud computing. Many services, such as e-mail, on-line banking, software for business environments are happening in large data centers. The emerging cloud-computing model also encourages more and more innovation in the construction of extensive and efficient data centers. In typical data-center networks there are tens of thousands of servers that are connected to each other and are faced with technical challenges, such as high power consumption and the complexity of control in the transition to ever higher bit rates. It is from this perspective that optical communications represent a huge potential.

Finally, we must not forget that new systems are created that directly integrate optical and wireless technologies, and which are in the future expected to exceed the limitations faced by current traditional wireless and fiber systems. An example is Radio-over-Fiber (RoF), wherein different "wireless" radio or even mm-wave signals are transmitted via fiber to a remote antenna or in the interiors of buildings [26]. In the case of a practical network with a large number of cellular end stations and very few central stations RoF transmission has a substantial advantage over current data transfer. In addition, RoF systems with a stabilized optical path and a constant signal delay in an optical fiber over long distances allow redundant and precise synchronization [27] also to telecommunications networks.

Another example of optical and wireless technologies are optical wireless links [28], where a new generation of light-emitting diodes are used for the illumination and data transmission at home or in the office environment. If optical wireless link is done by using ordinary visible light emitting source, which is used for illumination, we talk about Visible Light Communication (VLC) [29]. VCL systems can be done as single color modulation or by using RGB-type light emitting source where simple WDM is implemented. We expect that low-cost, simple and high-speed VCL approaches will open door to various applications [30].

5 Conclusion

This article presents the major research challenges in optical communication technology towards 2020 and beyond. Like in the past, optical communications are expected to be promoted in order to develop their unparalleled speed in the future. Optical communications will also continue to be subject to continuous development and sophistication that will apparently overcome new boundaries. In fact, the competition for higher speeds, higher quality and enormous capacity continues to dictate an extensive development in the field of optical communications. In this respect, multi-level modulations, polarization multiplexing, coherent detection and digital processing have an important position as they give support to each other and complement each other. It may be that the introduction of a flexible network grid with WDM brought about a revolution in the field of the management of telecommunications traffic. The present, well-established scheme of General Multiprotocol Label Switching (GMPLS) will be replaced by the Software Defined Networking (SDN) of telecommunication traffic. This will ensure the easier implementation of programmable transponders, increase network flexibility and simplify its management.

A glimpse into the future shows that a standard single-mode fiber will be withdrawn after three decades of successful application to a new type of optical fiber, like multimode optical fiber, which was abandoned in practice in the past. Future research efforts in the field of optical backbone networks will be aimed at tackling the problem of "fiber wall", with two trends from the field of spatial multiplexing in sight. Scientific research will focus on systems with multi-mode fiber, which allows optical MIMO transmission or few-core or even multi-core fibers. In the case of the proper management of cross-talk between individual cores, even a hybrid solution can be expected.

In the past the very successful WDM technology required 10 years from first laboratory experiments to an implementation in practice. It is difficult to predict how much time will be needed for spatial multiplexing to become commercialized. Before a certain technology is applied in practice, it is necessary to make scientific discoveries and laboratory tests to engineering solutions and standardization harmonizations. Physical feasibility is not the only relevant factor for today's telecommunications operators, they are primarily looking for economic viability. An exponential increase in data traffic it is not easy to meet with a linear increase in the costs for building and operating the network, which gives a particularly difficult task to researchers in the field of optical communications.

Acknowledgements

This work was supported by the Slovenian Research Agency (ARRS) as part of the "Algorithms and optimisation procedures in telecommunications" programme.

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Arrived: 10.4.2014
Accepted: 2.7.2014