称号及び氏名　　博士（工学）　坂本　泰志

学位授与の日付　平成 24 年 7 月 20 日

論　文　名　「A Study on All-Optical Signal Processing and Fiber Technologies for Capacity Enhancement of Optical Fiber Network」
（光ファイバーネットワークの容量拡大に向けた全光信号処理並びに光ファイバ技術に関する研究）

論文審査委員　主査　勝山　豊
副査　山下　勝己
副査　大橋　正治

論文要旨

The Internet has been developed rapidly and enables us to access enormous amount of information all over the world in a moment. Hence, the network carrying these data traffic and supporting the Internet plays an important role in today's information society. In the past decade, various services using broadband data communications have emerged and video-based applications become widely used in both public life and business. This has led to a great demand for a large capacity network for transporting the data generated at these applications. In addition to that, the number of Fiber-to-the-home service subscribers steadily increases year by year and have reached 20 million in 2010 in Japan. As a result, the traffic volume transported over the network grows rapidly and a throughput of the network have exceeds 1 Tbps at present. It is expected that the network traffic continues to increase in the future, thus revealing that the enhancing network capacity still calls for urgent attention.

To meet this capacity demand, the optical network has attracted much attention and developed owing to the low loss and broadband characteristics of single-mode optical fibers used as a transmission medium. Moreover, the wavelength division multiplexing (WDM) technology jumped the network capacity by several orders of magnitude because multiple data stream can transmitted simultaneously by the multiple carrier, the wavelength of which are different from each other. However, there are also some technical challenges to overcome toward the next generation ultra large capacity network.

An optical network consists basically of optical fibers and network nodes. In the network node, the received optical data packets are firstly converted into electrical signal and are stored in electrical random access memory in the node. Then, the destination address of the packets are extracted and finally forwarded to the suitable port after converting the electrical signal to optical signal again. However, this optical/electrical/optical conversion in the node is considered to become a bottleneck in the near future due to the limitation of the bandwidth of the electrical components, which is limited by tens of GHz at present. All-optical network have been investigated to overcome these limitation and realize a future high capacity transmission. In that network, the signal processing at the nodes such as signal storing or routing is carried out only in an optical domain. Thus, the signal processing speed is no longer limited by the electrical signal processing speed and resolves the bottleneck at the nodes. One of the key technologies to realize all-optical signal processing is optical buffering. Various optical buffering technologies have been investigated such as controlling speed of optical pulses using slow light phenomenon or variable fiber delay line. However, buffering time, bandwidth, and flexibility of optical buffers are not developed to a practical level and improving these characteristics of optical buffer is still of interest for recent researches.

The capability enhancement of optical fiber itself is another important factor toward the large capacity network. However, available bandwidth with low loss wavelength window of optical fibers is limited to an infrared wavelength region, and thus the capacity growth using WDM technology have slowed down because the bandwidth used by the WDM signals occupied low loss transmission windows. The multi-level signal format and digital coherent detection are the other transmission technologies to improve the spectral efficiency and increase the network capacity under the limited bandwidth. The higher signal to noise ratio (SNR) is required to transmit the signal and obtain a higher spectral efficiency in the above transmission. Although the higher SNR is obtained by increasing launching signal power into the optical fiber, the signal distortion induced by the nonlinear effect in optical fiber has occurred as the input power increased and imposed severe impairment for the transmission.

In recent year, many researches for mitigating fiber nonlinearity have been investigated. The simple way for reducing nonlinearity is using low nonlinearity fiber. This can be achieved by extending an effective area of the fiber, which is nearly equivalent to the core area of the fiber. However, the effective area and cutoff wavelength or macro bending loss of the optical fiber show the tradeoff relationship. Therefore, the enlarging effective area and reducing fiber nonlinearity is also limited by the other fiber characteristics.

The main objective of this thesis is to develop technologies contributing to enlarge the network capacity by enhancing the throughput at network node and increasing the bandwidth of optical fiber. For enhancing the throughput at the node, slow light and fiber delay line techniques have been investigated for realizing optical buffer in Chap. 2~4. The main technical challenges are to realize wideband operation and sufficient buffering time. The author focused on these issues and proposed novel techniques that realized simple configuration, wideband and large time delay. In addition, fibers with wideband and low nonlinearity have been investigated for increasing the capacity of the transmission line. The author focused on to use holey fiber as a transmission medium to overcome these issues, and realized wideband or low nonlinear transmission system using photonic crystal fibers. Conclusion of each section is summarized as follows.

Chapter 2 describes the pulse speed control techniques by using stimulated Brillouin scattering (SBS) slow/fast light for realizing flexible all-optical signal processing. First, a method for realizing pulse advancement induced by SBS in optical fibers without any pump sources is described to simplify the configuration of the fast light generation. A pulse advancement of 13.65 ns is achieved with this self-induced fast light method. Next, a method for realizing a slow light with a broadband flat Brillouin gain and low distortion slow light by using an optical frequency comb is described. It is shown that the broad and flat SBS gain with a bandwidth of over 200 MHz is obtained by using optical frequency comb. As a result, we achieved a relative 2.46 bit pulse delay while suppressing the pulse broadening.

Chapter 3 describes variable delay line technique using wavelength conversion and highly dispersive dual concentric core fiber (DCCF) to obtain a large time delay efficiently. The fabricated DCCF has a minimum dispersion of −2800 ps/nm/km, and has the potential to generate a 54-ns/km delay by employing wavelength conversion within the C-band. The signal quality is also evaluated by measuring the bit error rate characteristics of the delayed signals through the proposed delay line.

Chapter 4 describes the highly dispersive fiber design for the delay line. A dual concentric core fiber with six homogeneous air holes is shown to realize a large negative dispersion coefficient. It is numerically clarified that the dispersion property of the proposed DCCF can be controlled flexibly by adjusting the air-hole structure, and is experimentally realized the largest reported negative dispersion of −13200 ps/nm/km.

Chapter 5 describes a fiber design that incorporates a hole-assisted structure for suppressing SBS. The proposed hole-assisted fiber (HAF) has a simple structure with a low relative index difference and/or a small core radius. The impact of the core profile on the SBS gain spectrum is discussed and a 13.5 dB improvement in the SBS threshold with both a low SBS gain and a large effective area is numerically shown. Finally, the SBS suppression effect is confirmed experimentally by using the fabricated HAF.

Chapter 6 describes a wideband transmission and fiber nonlinearity reduction using photonic crystal fibers (PCF). First, the dense-WDM (DWDM) transmission in the O-band over a 24 km PCF realized by using an optical frequency comb based multi-carrier source is described and it is shown that a 10 Gbps x 15 DWDM transmission over a 24 km PCF with a low power penalty is successfully demonstrated. Next, the modal dispersion compensation technique for low nonlinear transmission using PCF with ultra large effective area is described. The advantage of few-mode PCF for realizing a larger effective area (A_{eff}) is numerically shown, and finally a transmission over a large-core two-mode PCF with A_{eff} >280 μm^2 is successfully demonstrated.

The capacity enhancement is essential to accommodate the future large amount of traffic. This study can be expected to contribute to realize such a large capacity optical fiber network by the improvement of network nodes and optical fibers.

審査結果の要旨

本論文は、光ファイバーネットワークが今後とも増加し続ける情報を送信できるよう、全光ネットワークノードおよび、より広帯域な光ファイバーについて行った研究結果をまとめたものである。ネットワークノードでは、データの転送先判断等のために光信号を電気信号に変換するが、電気処理の速度に限界があるため、より速い全光処理が必要になる。これには光領域でのバッファが必要であるが、この実現にむけスローライト技術とチューナブル光遅延線を研究し、広帯域かつ十分なバッファリング時間がとれることを実証している。広帯域な光ファイバーについては、ホーリーファイバー等について研究し、強い光パワー入射に伴う光ファイバーの非線形性を減少させ、低非線形性伝送システムを実現している。得られた主な結果は、以下の項目に要約できる。

(1) 全光ネットワークにむけ、誘導ブリュアン散乱による光パルス速度制御技術を検討し、パルス幅を増加させずに相対的に 2.46 パルス遅延を達成するとともに、波長変換と高分散性同心 2 重コアファイバー(DCCF: Dual Concentric Core Fiber)を用いた可変遅延線技術により、54 ns/km の遅延を実現できる可能性を示した。

(2) DCCF が遅延線に有効なことから、6 つの均一な空孔をもつ 2 重コア同心ファイバーを提案し、このファイバーの設計法を明らかにし、大きな負の分散係数をもつことを示した。この結果、提案した DCCF は、空孔の構造を変化させると分散性を制御できることを示し、負の分散値が現状の最大となる —13,200 ps/nm/km を実現した。

(3) 高光パワー伝送時に生じる誘導ブリュアン散乱を抑えるため、ホールアシストファイバーのコア形状を検討し、提案した構造により誘導ブリュアン散乱のしきい値を 13.5dB 改善できることを理論的に示すと共に、提案したファイバーを実際に作成し、実験によって想定した効果があることを示した。

(4) 広帯域な光伝送システムとして、フォトニッククリスタルファイバー(PCF: Photonic Crystal Fiber)を対象とし、10 Gbps x 高密度 15 波長多重により、24km 長の PCF に対し低パワーペナルティで光伝送が可能なことを実験で示した。

以上の結果は、光ファイバーネットワークの帯域を増大させ、今後の情報増加に対応する上で必要となる基礎的な技術を進展させており、本分野の学術および産業上の発展に寄与するところ大である。また、申請者が自立して研究活動を行うのに必要な能力と学識とを有することを証したものである。
学位論文審査委員会は、本論文の審査ならびに学力確認試験の結果から、博士（工学）の学位を授与することを適当と認める。