平成 12 年度博士論文要旨

平成9年度入学　大学院博士後期課程　システム情報工学専攻　電子工学講座

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論文題目　Numerical Simulations of Four-Wave Mixing among Short OpticalPulses in Semiconductor Optical Amplifiers by the Beam Propagation Method

和訳題目　半導体光増幅器中の短光パルス間4光波混合特性のビーム伝搬法による数値解析

- **Abstract**

Optical functional devices using the four-wave mixing (FWM) in a semiconductoroptical amplifier (SOA) have many important features such as having an opticalgain, operations with relatively low optical input power, small size, andfeasibility for large integrations. These are expected as all-optical deviceshaving important functions such as wavelength conversion, optical demultiplexing(DEMUX), optical phase conjugation, and optical sampling. The analyticalapproach is indispensable in order to design highly efficient and high-speedFWM conversion devices. Existing methods did not consider the group velocitydispersion for the analysis of FWM, which may be especially important forthe large pump-probe detuning and SOAs long device length. Without thiseffect, the FWM conversion efficiency may appear to be overestimated. Themain results, we have obtained are as follows:

(1) We have numerically analyzed the nondegenerate FWM among short opticalpulses in an SOA by the finite-difference beam propagation method (FD-BPM).In simulation, we have used the nonlinear propagation equation taking intoaccount the gain spectrum, the dynamic gain saturation that depends on carrierdepression, carrier heating, and spectral hole-burning, group velocity dispersion,self-phase modulations, and two-photon absorption. To analyze the FWM inan SOA, the evolution in time and spectral domain of two input optical pulseswith different frequencies during propagation has been calculated. Fromthe simulation, it has become clear that this method is very useful techniqueto simulate FWM characteristics in SOAs. We also found that wavelength dependencyof the gain is crucial if the detuning is larger than 1 THz.

(2) We have analyzed all-optical DEMUX characteristics based on FWM inSOAs by using the FD-BPM. From the viewpoint of the ON-OFF ratio, we haveobtained the optimum pump pulsewidth of 1~3 ps for the 1 ps, 250 Gbit/sprobe pulses. The shorter limit of the pulsewidth arises from the detuningbetween the pump and probe frequencies, which is determined by the gainbandwidth of the SOA. To achieve the faster DEMUX operation, the SOA withbroader gain bandwidth is required. We have also simulated the pattern effectson the FWM signal. The power fluctuation of the FWM signal can be reducedby using the strong pump pulse or/ and the weak probe pulse. The energyfluctuation of the FWM signal decreases to less than 1% for a 30-bits, 250-Gbit/sinput probe pulse train with a pulse energy of 0.01 pJ. This small fluctuationdoes not disturb the

DEMUX operation.

(3) We have analyzed optical phase-conjugate characteristics of picosecondFWM signals in an SOA by the FD-BPM. We have shown that the optical phase-conjugatecharacteristics of the FWM signals strongly depend on the input pump pulsewidths.As one typical example, we have demonstrated that the SOA acts as a nearlyperfect phase-conjugator for a 10 ps input pump pulse and the ~2.2 ps linearlychirped input probe pulse. When the pulsewidth of pump pulse decreases,the minimum compressed pulsewidth is obtained using the shorter length fiberthan the input fiber, having the same value of group velocity dispersionas that of the input fiber. For a much shorter pump pulse, like 1 ps, theshort FWM signal can be obtained due to the gating characteristics of theFWM. However, only a part of the phase information is copied to the FWMsignal due to such gating characteristics. The phase information is alsodeteriorated due to the fast nonlinear effect in SOAs. Thus, the pulsewidthis not compressed by the dispersive medium. Besides the above results, Wehave also analyzed the propagation characteristics of nonlinear short opticalpulses in an SOA by the FD-BPM. The saturation energy decreases with the decrease in the input pulsewidth.In temporal domain, the output pulses peak positions are shifted to theleading edge due to the gain saturation of the SOAs. The output spectraare red-shifted and the dips are observed at the higher frequency side inthe
frequency spectra. We have numerically analyzed the time-delay characteristicsof FWM among short optical pulses in an SOA by the FD-BPM. With the increasein the input pump energy, the optimum time-delays shift to the probe first(negative) direction. When the input probe energy increases, the optimumtime-delays are shifting from the probe first (negative) to pump first (positive)direction. The shift of the optimum time-delay drastically decreases whenstrong input pump pulse is injected. FWM conversion efficiency decreaseswith the increase of input probe energy. The increase in the pump energylets the efficiency increases. On the contrary, FWM conversion efficiencydecreases with increasing the input probe energy. If the time-delay is optimizedfor each input probe energy then the decrease of conversion efficiency forstrong input probe energy can be reduced. As a result of the simulation,we conclude that the FWM conversion efficiency increases with the optimumtime-delays between the pump and probe pulses.

（和訳要旨）

半導体光増幅器は光学利得を持ち、他の光増幅器と比べ小型であること、他の半導体素子とのモノリシックな集積化が期待できることから、光通信・光情報処理において重要な素子として広く研究されている。 近年、この半導体光増幅器中の 4 光波混合現象を利用した超高速光多重・多重分離(DEMUX)素子、波長変換素子、光位相共役素子等が実験を中心に研究されている。

本研究は、半導体光増幅器中の短光パルス間の 4 光波混合現象をビーム伝搬法を用いて解析することにより、4 光波混合特性が素子構造や動作条件にどのように依存するかを明らかにすること、および DEMUX 特性や位相共役特性を明らかにすることを目的としている。解析手法にビーム伝搬法を用いることによって、半導体光増幅器中を伝搬する光の様子が解析できること、光の位相情報を得ることができるなどの特徴もある。本研究で得られた主な結果は次のとおりである。

⑴ 差分ビーム伝播法が半導体レーザ増幅器中の短パルス光間 4 光波混合特性を解析する手法として有用であることを基本特性の解析から示した。又、短光パルス間の 4 光波混合特性は半導体レーザ増幅器の利得帯域幅に大きく依存することがわかった。

⑵ 時間多重分離特性を計算し、最適なパルス幅を求めた。より高速の時間多重分離を行うためには、半導体レーザの利得帯域幅を広くする必要があることがわかった。又、パターン効果はポンプ光を強くすることにより、実用上問題がないレベルまで小さくできることがわかった。

⑶ 半導体レーザ増幅器中を短光パルスが伝播するとき生ずる自己位相変調について明らかにすると共に、4 光波信号光の位相共役特性について検討した。その結果、比較的長いポンプ光を用いることにより、位相共役特性が向上することがわかった。又、自己位相変調効果の位相共役特性への影響についても検討した。