博士論文審査結果の要旨

博士論文審査委員会

主　　査	堀口　常雄	審査委員	加島　宜雄
審査委員	小池　義和	審査委員	齋藤　敦史
審査委員	小山田　弥平		

氏　　名	Mohd Saiful Dzulkefly Bin Zan
論文題目	A Study on the Coding Techniques for Phase-Shift Pulse Brillouin Optical Time Domain Analysis (PSP-BOTDA)Fiber Optic Sensor

〔論文審査の要旨〕

提出された博士論文について詳細かつ厳正な審査を行い、審査委員全員一致で最終審査を合格と判定した。審査の模様は以下の通りであった。

審査は、公聴会を兼ねた１時間の論文の発表と、１時間の質疑応答、審議によって行った。予備審査で指摘された、改善項目、追加の検討、および修正項目を中心に審査が行われた。具体的には以下の通り。

・提案された４種類の複合符号の比較検討に関しては、予備審査段階では定性的な議論にとどまっていたが、最終審査論文では、新たな章を設け、測定時間、距離分解能、測定距離の各観点から定量的に比較検討され、それぞれの適用領域が明確になった。
・提案された項目の一つである dual Walsh 符号の使用に関しては、予備審査段階では計算機シミュレーションだけであったものが、最終審査では実験による検証結果も追加され、その有効性がより明確になった。
・提案技術と類似の技術の解説が追加され、提案技術の位置付けが明確になった。
・分布型光ファイバセンサの特性の一つである距離分解能の評価方法が統一されて議論された。
・用語が統一された。

また、以下の意見があった。

・Walsh 符号の応用、Dual Walsh 符号の提案と適用、光変調器駆動電気信号の工夫など、申請者の発案事項のオリジナリティに関して、さらにアッピールするように発表したほうが良かった。

審査の模様は以上の通りであり、予備審査で指摘された事項はすべて改善、追加、修正された。一部、発表方法に改善の余地は残されているが、最終の博士論文は、優れた成果が含まれた非常に濃い内容となっており、学位授与にふさわしいものと認められるので、合格と判定とした。

（様式第６号）

論　文　要　旨

2014年1月9日

※報告番号	甲　第　157　号	氏　名	Mohd Saiful Dzulkefly Bin Zan（モハマド　サイフル　ズルケフリ　ビン　ザン）

主論文題名

A Study on the Coding Techniques for Phase-Shift Pulse Brillouin Optical Time Domain Analysis (PSP-BOTDA) Fiber Optic Sensor

内容の要旨：

BOTDA (Brillouin optical time domain analysis) is a technique used to measure distributed strain and temperature along a fiber optic cable with high accuracy and sensitivity by utilizing the occurrence of optical scattering in the fiber called stimulated Brillouin scattering (SBS). The interaction among the pulsed pump light, the counter propagating continuous-wave form probe light and the acoustic wave in the fiber generates the back-scattered light through SBS process. Through this process, energy transfer occurs from pump to probe when their frequency difference is tuned to the Brillouin frequency shift (BFS) of the fiber. Since BFS linearly increases with the increase in strain and temperature, BOTDA can measure local changes in the strain and temperature along the fiber. BOTDA has found its application in the field of civil engineering for structural health monitoring of large structure such as buildings, dams, bridges etc.

Optical signal-to-noise ratio (SNR) and spatial resolution are the important parameters in characterizing the performance of BOTDA. In this study, the employment of combined codes that simultaneously use return-to-zero (RZ) and non-return-to-zero (NRZ) pulses to modulate the pump light of BOTDA is proposed for improving these parameters. Two types of coding systems called Golay code and Walsh code are introduced. Golay code uses auto-correlations while Walsh code uses Hadamard transform to decode the measured signals. There are four coding systems proposed in this study; dual Golay codes, dual Walsh codes and the two types of combined Walsh and Golay codes.

The proposed systems above offer higher SNR measurement than the conventional method that uses only RZ- or NRZ pulses. From the simulation and experimental results for code duration of 1ns, when the code length for NRZ pulses is fixed at a certain value for all combined codes cases, the SNR improved linearly with the square-root of the code length of RZ pulses. However, when the code length for RZ pulses is fixed and the code length for NRZ is increased, the SNR improvement reached maxima of 3dB when the total code duration of NRZ pulses was 8ns (code length 8bits x 1ns), and the amount of improvement started to decrease for longer NRZ code length. The limitation in the SNR improvement is caused by the decrease in the measured Brillouin signals, which is induced by the attenuation of acoustic wave amplitude during SBS. In the case of silica fibers, the time constant of the acoustic wave is 9ns. Therefore, in order to obtain maximum SNR improvement for both Walsh and Golay codes, the total code duration for NRZ pulses must be set to around 9ns.

In terms of spatial resolution, when the total code duration for NRZ pulses is around or less than

※印欄記入不要

（様式第６号）

論　文　要　旨

2014年1月9日

※ 報告番号	甲 第 157 号	氏　名	モハマド サイフル ズルケフリ ビン ザン Mohd Saiful Dzulkefly Bin Zan

the time constant of the acoustic wave, the spatial resolution of 10cm was successfully obtained for coded pulse of duration of 1ns case and for all combined codes cases. However, for dual Golay codes and combined Walsh (RZ) and Golay (NRZ) codes cases, the spatial resolution is degraded when the total code duration of the NRZ pulses exceeds the time constant of the acoustic wave (9ns). The decrease in the acoustic wave amplitude has induced decrease in the received Brillouin signal in the order of NRZ coded pulses, resulting in the appearance of side-lobes in the signal when decoded by auto-correlations for Golay code.

In contrast, for dual Walsh codes and combined Walsh (NRZ) and Golay(RZ) codes cases, decoded signal with excellent spatial resolution was attained even when the total code duration of NRZ pulses exceeds the time constant of the acoustic wave. This is because Hadamard transform process in decoding the Walsh codes is robust against the amplitude variation in the received Brillouin signal.

In conclusions, the simultaneous use of RZ- and NRZ pulse codings proposed in this research has contributed to the achievement of higher SNR than that of using only RZ- or NRZ pulse coding. The SNR increases linearly with the square-root of the code length for RZ pulses. While for the NRZ pulses, the maximum SNR is limited by the time constant of the acoustic wave, in this case 9ns. Therefore, for coded pulse duration of 1ns, the maximum code duration of NRZ pulses that can be used to achieve maximum SNR is 8ns (8 bits x 1ns). In addition, in terms of spatial resolution, it is concluded that the assignment of Walsh codes to the NRZ pulses offers better spatial resolution measurement than that of assigning Golay codes, even when the total code duration of the Walsh codes exceeds the time constant of the acoustic wave. Therefore, the combined code systems proposed in this thesis provide the method to have a balance of the tradeoff between the spatial resolution and the measurement time of the PSP-BOTDA in accordance to the measurement condition.

※印欄記入不要