Transient Control using Controlled Chaotic Instabilities in Brillouin-Active Fibers based Neural Network in Smart Structure

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Summary

In this paper the transient control using effect of steady and relaxation oscillation in optical fiber based on neural networks and hardware implementation is described. The inherent optical feedback by the backscattered Stokes wave in optical fiber leads to instabilities in the form of optical chaos. The controlling of chaos induced transient instability in Brillouin-active fiber based smart structures leads to neural networks with steady and relaxation oscillations. Controlled chaotic instabilities can be used for optical logic and computations and optical sensing. It is theoretically possible to apply the multi-stability regimes as an optical memory device for encoding and decoding and complex data transmission in optical systems.

Key words:

Optical Fiber Sensing, Chaotic Instability, Neural Networks.

Introduction

Optical fibers based on neural networks application and hardware implementation have been extensively used in optical systems [1], [2]. Recent interest has been also focused on using optical fibers as sensors since fiber parameters are sensitive to the fiber immediate environment [3], [4]. Important advances have been made in reducing optical losses in fibers, so the light signal can propagate in long haul transmission without requiring inline amplifiers. Large input signals are required leading to nonlinear optical phenomenon in optical fibers, when signal power exceeds threshold. Specially, in the case of stimulated Brillouin scattering (sBs), part of the signal power is converted into reflected lightwave, traveling backwards towards the input of the fiber. The backward scattering nature of Brillouin scattering has long been viewed as an ultimate intrinsic loss mechanism in long haul fibers, since Brillouin threshold decreases with increasing effective fiber length. On the other hand, the very backscattering nature of this process and the existence of a threshold, provide potential optical device functions, such as optical switching, channel selection, amplification, sensing, arithmetic and neural functions in optical signal processing, and neural network applications and hardware implementation. The theoretical and physical background of this nonlinear process has been well explained [5],[6]. The backward scattering scheme based on neural networks in optical fiber is shown in Figure 1.

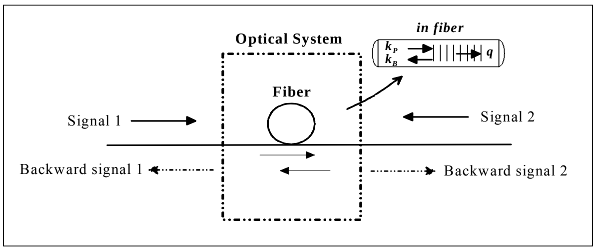

Fig. 1. Hardware implementation based Brillouin-active fiber with forward/backward propagation Stokes waves

Active device in optical systems generally require the employment of nonlinearity, and possibly feedback for increased device efficiency. The presence of nonlinearity together with intrinsic delayed feedback has been repeatedly demonstrated to lead to instabilities and optical chaos [7], [8]. This phenomenon has extensively investigated by us for its potential detrimental effect to the Brillouin fiber sensor [9], [10].

A smart structure can potentially implement a massively parallel computational architecture with its attendant reduction in processing time while managing the complexity of the system, i.e. the sensing/actuation grid. Our sBs network would learn the correct "algorithms" by example during training and have the ability to generalize to untrained inputs after training is completed. The inputs to the network are the fiber optic signal outputs, and the network outputs are the control signals for actuation controls. The true advantage of this system for application to smart structures lies both in its capability to analyze complex signal patterns and its speed in generating the appropriate control signal for the actuators. The key lies in the implementation of a neuron operation using sBs in optical fiber.

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2 SBS Based Neuron

An artificial neuron, used in neural network research, can be thought of as a device with multiple inputs and single or multiple outputs in hardware implementations. The inputs to a neuron are weighted signals. The neuron adds the weighted signals, com-pares the result with a preset value, and activates if the sum exceeds threshold. Neuron-type operations can be performed by an optoelectronic system that uses sBs for the weighted summation required in a neuron. Weighting can be achieved by optical summation and subtraction, conveniently carried out in an optical fiber using sBs. Weighted additions and subtractions are needed in many situations. For example, a neuron performs weighted summation of the incoming signals. The performance of such a device will enhance if it operates optically. We propose to study a system that can perform the practical implementation of a Brillouin-active fiber for optical neural net, neural function by exploiting the acousto-optic nature of the sBs process [9],[10].

In the nonlinear optical phenomenon, the system's combined weighted signals also produce an output if the weighted sum is greater than the threshold. A typical neuron, based control signal with input and output systems, is illustrated in Figure 2.

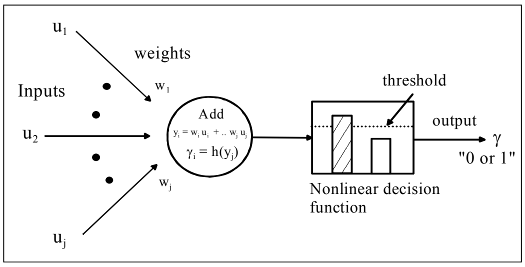

Fig. 2. A simplified multi-layered neural network. The networks have physical resemblance; optical fiber networks to nerve system and neural networks.

A theoretical SBS based neural network, utilizing sBs threshold sensing with an embedded sensor is shown in Figure 3. The arithmetic building block of energy addition and subtraction (normally difficult to perform), as in Fig.3, can conceivably be accomplished by the sBs process, which involves energy transfer between waves. Thus, if two waves at a frequency difference equal to the Stokes downshift of the fiber propagate in the fiber in opposite directions, then energy is "subtracted" from the higher frequency wave and "added" to the lower frequency wave. If three waves are present in a fiber with equal Stokes shifts, then the wave at the middle frequency will receive energy from the higher frequency wave and lose energy to the lower frequency wave. Practical implementation of this scheme calls for all the waves to be generated by the same laser, since the Brillouin shifts are typically very small.

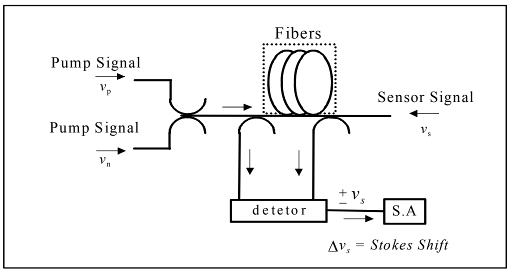

Fig. 3. SBS implementation of threshold logic with optical logic networks

3 SBS Threshold Logic

Since the Stokes shift is small, the wavelengths in each wave λ_p, λ_n, and λ_s are almost equal [11]. With these assumptions, the nonlinear coupled equation can be written as,

$$\frac{dI_p}{dz} = -\alpha I_p - g_B I_p I_s \qquad (1)$$

$$-\frac{dI_s}{dz} = -\alpha I_s + g_B I_s I_p - g_B I_n I s \qquad (2)$$

$$\frac{dI_n}{dz} = -\alpha I_n + g_B I_n I s \qquad (3)$$

where I represents wave intensity of the pump "p", the backward Stokes wave "s" and the acoustic wave "n", and α and g_B are respectively the fiber attenuation coefficient and Brillouin gain coefficient for all the waves. In the basic optical neuron-type setup shown in Fig. 3, the input-output conditions of the waves are given as follows:

$$I_p(L) = I_p(0)\, e^{-\alpha L} \qquad (4)$$

$$I_n(L) = I_n(0)\, e^{-\alpha L} \qquad (5)$$

$$I_s(0) = I_s(L)\, e^{-\alpha L\, g_B L_{eff} \Delta I} \qquad (6)$$

where $\Delta I = I_p(0) - I_n(0)$ and $I_p(0)$ is the pump transmission. If the net gain of the sensor signal is close to 0 dB, then $I_s(L) \approx I_s(0)$ so that $P_s(0) \approx P_s(L) << \alpha A_{eff}/g_b \le p_p(0)$, where we have used $I = p/A_{eff}$, in which $A_{eff} = \pi r^2$ is the effective cross sectional area of the fiber, and p is the power. The ratio $\beta = P_s(L)/P_s(0)$ is on the order of 0.01 or less. Using pump power level for 0 dB gain, we can estimate the pump power value, if p_s = 1 mw, the pump power $p_n(0)$ required will be 1W. The intensity level of each wave is set below the SBS threshold ($I_{th} = 21/g_b L_{eff}$) in order to avoid the generation of backward Stokes from spontaneous scattering. The stokes gain v_s versus total pump power difference $p_p(0) - p_n(0)$ is shown in Figure 4. The gain can be converted to loss and vice versa, simply by changing the pump power levels. The output state of a neuron can be changed by changing one or both input pump intensities. The threshold of the neuron can be controlled by changing the power launched in the stokes signal as shown in the Fig.4.

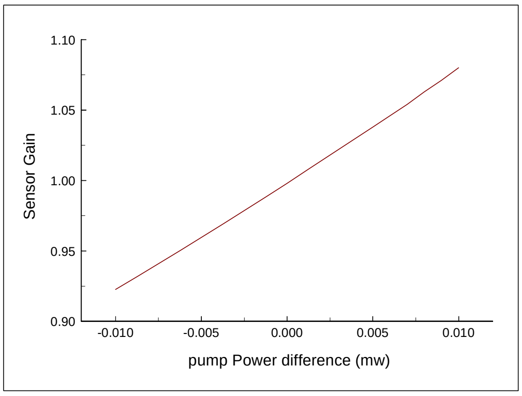

Fig. 4. Backward Stokes signal (vs) vs. pump power difference $p_p(0) - p_n(0)$

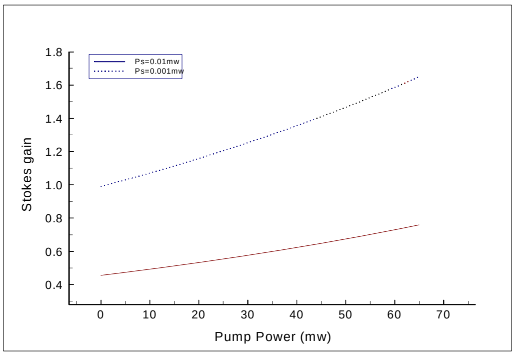

Fig. 5. Net gain of backscattered Stokes signal vs. as a function of pump power.

Assuming α = 0.2 *dB/km* at 1.03 μm and a fiber core diameter of 8μm by 3M. The net gain of stokes signal as a function of the pump power is shown in Figure 5**,** It shows a change in pump power as a change in the 0 *dB*(or 1.0) gain point. The threshold of the neuron can be controlled by changing the power launched in the Stokes signal. Thus different neurons can have different thresholds. For a single mode optical fiber, the threshold incident laser power required is on the order of 10 *mw* for 1*Km* fiber. Thus, the sensor power level should be ~10 *mw*, and the pump power level should be greater than 10 *mw*

3 SBS Network Implementation

A practical sBs logic implementation of theoretical neuron based neural networks and hardware implementations, as shown in Figure 6, calls for all the waves to be generated by the same laser. A stabilized *cw* probe laser operating was used as a pump source for low scattering losses in the fiber, yielding a ≈13 *GHz* Brillouin scattering shift. Detection is also achieved with a *IR* Photodetector Set (New Focus and an amplifier with ~*ps* impulse response) connected to a *HP* Oscilloscope.

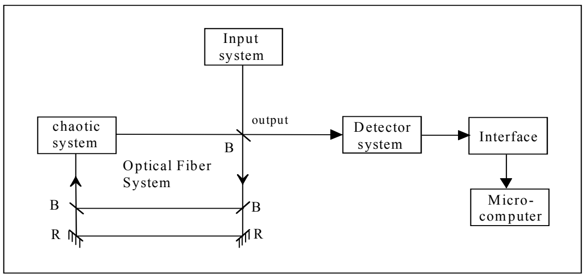

Fig. 6. Schematic diagram for controlling chaos induced instability in optical fiber based neural network system. The optical implementation included a chaotic system configured.

Some levels of temporal instability and chaotic behavior in the backscattered intensity and also in its spectral line shift have been observed(see Fig.7). It is thus essential to know whether insertion of an amplifier will further destabilize the optical system. Since our proposed implementation is based on monitoring the Brillouin spectral line shift with varying temperature and strain, the origin of the temporal chaotic behavior must be understood and its correlation to spectral line shift examined. The Brillouin signal is simultaneously displayed on a fast scope for better interpretation of the temporal process that leads to pulse train generation. The detected signal will also be viewed on a Microcomputer for comparison. When the pump power reaches a threshold value, a temporal structure arises in the backward signal, consisting of a periodic train of Brillouin wave pulses as shown in Figure 7(a). The temporal repetition rate of which corresponds to a pulse round-trip time in the fiber-ring taken to be less than 10 *nsec*. The Brillouin pulse train amplitudes remain unstable, particularly just below pump threshold. When the observation is made using a long time scale (100μsec/division), the Brillouin output exhibits randomly distributed trains of periodic pulses. Partial stabilization of amplitude fluctuations is achieved as laser pump power approaches maximum value. These experimental features are shown in time domain in Fig. 7 (b) through (d). Instability can also occur at threshold power. The temporal evolution immediately above this threshold is periodic and at higher intensities can, for the case of a relatively broad

Brillouin linewidth, become chaotic (see Fig.7 (d)). In the data presented, mechanical vibrations could be partially responsible for these Brillouin temporal instabilities, because small amplitude fluctuations with similar frequencies were observed below the Brillouin threshold. The results attribute these Brillouin instabilities to phase fluctuations between direct and coupled pump intensity in the optical fiber systems.

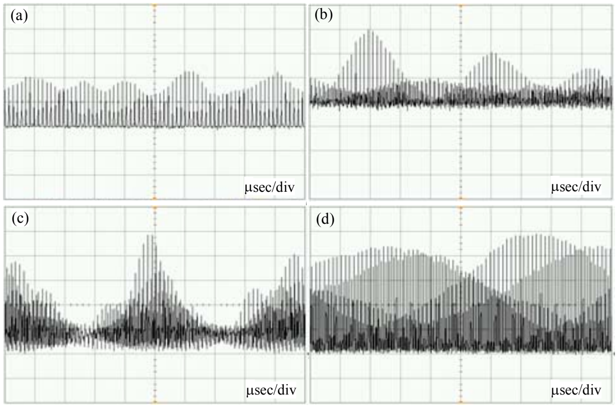

Fig.7. Temporal structures of SBS instability vs. time; (a) before threshold, (b) immediately threshold, (c) above threshold, (d) high threshold with chaos. The whole time scale is [μsec/division].

At low power, the Brillouin instability can occur below sBs threshold. This is much lower than the power required for normal Brillouin process, involving single pump power. The temporal evolution immediately above threshold is periodic and at lower intensities can become chaotic. We propose to employ continuous optical feedback for control in which coherent interference of the chaotic optical signal with itself, when delayed, can achieve signal differencing for feedback. If suppressing by attractor proves to control chaos then, suppressing under natural chaos can be exploited as a means of sensing structural chaos.

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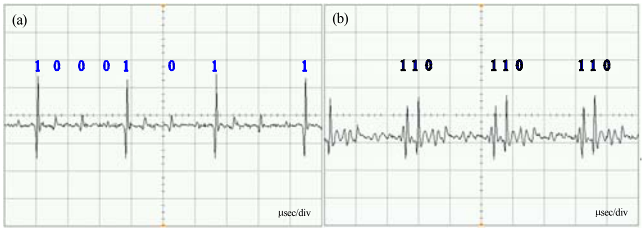

Fig. 8. Transiently controlled sBs chaos induced instabilities at immediately above threshold (a) high above threshold (b). The examples of sequence of suppression are assigned by ‘0’ and ‘1’ symbols.

If suppressing by attractor proves to control chaos then, suppressing under natural chaos can be exploited as a means of sensing structural chaos. The examples of sequence of suppression are assigned by ‘low level’ and ‘high level’ states. Multi-stable periodic states, as shown in Figure 8 (a) and (b), can lead to logic ‘0’ or ‘1’ and can in principle create large memory capacity as input bit streams in transmission data network systems.

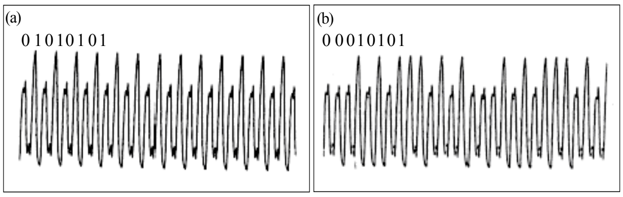

Fig. 9. Theoretically possible sequences of bifurcation are assigned by low level, high level symbols.

The examples of sequence of suppression are assigned by ‘low level’ and ‘high level’ states as shown in Figure 9 (a) and (b). Its implementation still requires much engineering improvements, such as arriving at a spatial resolution that is comparable to the references or speckle, and suppression of its tendency to chaos.

4 Conclusions

We studied that the transient control with steady and relaxation oscillation using controlled chaotic instabilities in optical system leads to neural networks with multistable periodic states. Control of SBS chaos-induced transient instability in optical systems leads to logic ‘*on*’ or ‘*off*’ with multistable periodic states. It is theoretically possible to apply the multi-stability regimes as an optical memory device for encoding/decoding messages and complex data transmission in optical communications systems.

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