論 文
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광섬유링센서에서 유도되는 브루앤파의 혼돈 및 비안정화 현상

Chaotic and Instability Effects in Brillouin-Active Fiber-Ring Sensor

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Abstract – In this paper the effect of chaos induced instability in Brillouin-active fiber-ring sensor is described. The inherent optical feedback by the backscattered Stokes wave in optical fiber leads to instabilities in the form of optical chaos. The paradigm of optical chaos in fiber serves as a test for fundamental study of chaos and its suppression and exploitation in practical application in communication and sensing. At weak power, the nature of the Brillouin instability can occur at before threshold. At strong power, the temporal evolution above threshold is periodic and at higher intensity can become chaotic. The threshold for the Brillouin instability in fiber-ring sensor is much lower than the threshold of the normal Brillouin instability process.

Key Words : Nonlinear Effect, Brillouin Scattering, Brillouin-Active Fiber-Ring Sensor, Brillouin Chaotic Effect, Chaos Induced Instability.

1. Introduction

It is well known that optical fibers have potential for various uses in the optical communication and systems [1-4]. Recent interest has been focused on using optical fibers as sensors especially each fiber being capable of reacting and measuring changes in its immediate environment[5-6].

Important advances have been made in the purity of the optical fibers themselves, reducing optical losses, so the light signal can propagate in long haul transmission without requiring in-line amplifiers. For using on the communication and optical system with long haul transmission, the semiconductor and fiber optic amplifiers have used. However, these currently electrical and optical amplifiers still constitute lossy interfaces that backscattered incident light signal. Large input signals are thus required and these lead to nonlinear optical phenomenon in optical fibers. If the input power into fiber exceeds the some critical threshold level, then a nonlinear effect can occur, which may be converted into reflected lightwave, traveling backwards towards the fiber transmission line. The theoretical and physical background of this nonlinear process has been well explained [7-8].

The nonlinearity that is most readily present in the optical fiber is Brillouin scattering and the Kerr effect. Brillouin scattering is light reflection by laser induced acoustic wave in the fiber. Brillouin activity in singlemode fibers has been extensively investigated theoretically and experimentally by many others[8-11]. 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. The backward scattering scheme in optical fiber is shown in Figure 1.

An active device in optical systems generally requires the employment of nonlinearity, and possible feedback for increased efficiency in device function. The presence of this nonlinearity with intrinsic delayed feedback has been also repeatedly demonstrated to lead to instabilities and chaos in optical fiber transmission lines. The combination of nonlinearity and optical feedback in optical transmission lines, is a prescription for inherent deterministic instabilities that may ultimately lead to optical chaos in optical fiber[11-14].

In this paper the effect of nonlinear limitations on the fiber optical systems, in the form of instability and chaos on the Brillouin-active fiber-ring sensor is described.

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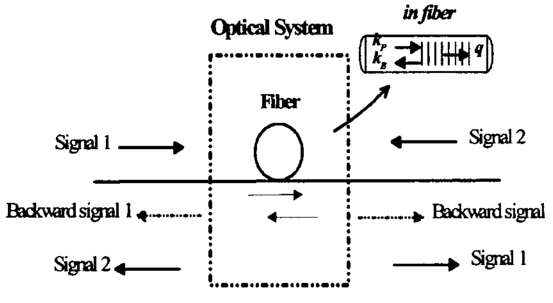

Fig.1. Brillouin-active fiber configuration with counter-propagation Stokes waves.

2. NonlinearEffectinBrillouin-ActiveFiber

Brillouin scattering has the lowest threshold among nonlinear optics phenomena and hence has attracted the greatest interest in small core, low loss single mode fibers for next-generation network and systems. It turns out that Brillouin scattering is a paradigm in the field of nonlinear dynamics in any systems, in which a signal originating from noise evolves into deterministically dynamic behavior through a nonlinear interaction.

If the optical power launched into the fiber exceeds some critical threshold level, then Brillouin effect can occur. The Brillouin effect causes a significant proportion of the optical power traveling through the fiber transmission line to be converted into a reflected lightwave, shifted in frequency, traveling backward direction. The Brillouin effect can occur in a single pass through long fibers of low loss single mode fiber with launched power levels only a few milliwatt, which is within the envisaged operating range of optical systems. This effect can be detrimental to an optical transmission system in a number of ways: severe additional signal attenuation, by causing multiple frequency shifts in some cases, and high intensity backward coupling in the transmission optics. The characteristics of backward Brillouin scattering in fiber, such as frequency shift, linewidth, gain, and threshold can be established using same approach as that for a bulk materials. A typical optical spectrum of the backscattered signal in Brillouin shift, showing a narrow single-frequency output with a linewidth of less than 20 *MHz* [7].

The governing equation for the Brillouin threshold in a fiber is $G_B P_o^{cr} L_{eff} / A_{eff} = 21$ (for open-ended fiber) and $G_B P_o^{cr} L_{eff} / A_{eff} = 0.1 \sim 1$ (for a fiber-ring) [7]. The Brillouin - active fiber-ring threshold theoretically can be lowered by 200 times. Above equations provide the basis of an additional enhancing technique. Taking G_B, A_{eff} to be given, then the P_o^{cr} and L_{eff} product is lowered to 200 times going from the open-ended fiber to a fiber-ring. This means lowering P_o^{c} or shortening L_{eff}. In our sensor application, minimum L_{eff} is essential. On the other hand, in optical logic, fiber length is not important valuable, while minimum P_o^{cr} is important. Hence, in both cases, lowering of $G_B P_o^{cr} L_{eff}/A_{eff}$ from 21 to 0.1 is the key to practical implementation of Brillouin scattering.

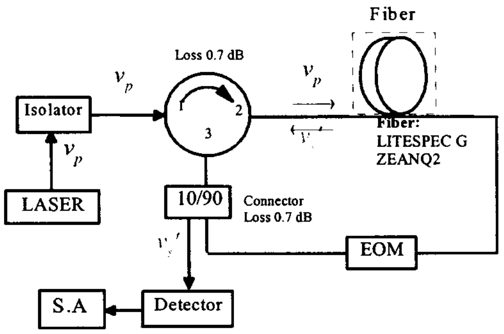

Fig.2. Configuration of Brillouin-active fiber-ring sensor for low threshold gain spectrum. EOM is Electrooptical modulator and SA is RF Spectrum Analyzer.

Fiber-ring configurations greatly reduce the fiber sensor length required. The Brillouin-active fiber-ring scheme for low threshold is shown in Figure 2. The main advantage of the fiber-ring lies in the recurrent geometry, in which the backscattered Stokes wave is repeatedly amplified by the incoming pump wave at the input port that is not attenuated by fiber loss, as opposed to the linear fiber amplifier, in which the Brilllouin wave encounters a progressively depleted forward traveling pump wave.

3. BrillouinChaoticEffect

Instabilities are unavoidable in Brillouin scattering due to its intrinsic nonlinearity and feedback. We have designed a setup for analyzing Brillouin instabilities in a fiber-ring configuration. The main advantage of fiber-ring has already been given above. The experimental setup for analyzing chaos in Brillouin-active fiber-ring is shown in Figure 3.

A stabilized *CW* probe laser operating at 1310 *nm* was used as a pump source, its operation at 1310 *nm* providing low scattering losses in the fiber, yielding a 12 *GHz* Brillouin scattering shift. We use a fiber length of 4.28 *km* LITESPEC- G-ZEANQ. Detection is also achieved with a 25*GHz* IR Photodetector set (New Focus and a amplifier with 20*ps* impulse response) connected to a Infiniium Oscilloscope.

A single pump signal from the laser is sent to the optical system through a coupler. An isolator is installed to prevent a backward pump signal, from getting into the laser cavity and disrupting the performance of the laser.

The pump signal travels through the long fiber to an embedded sensing fiber. If the pump signal launched into the fibers exceeds some critical threshold level, then Brillouin scattering can occur. In this process, the input pump signal travelling through the fibers may be converted into a second wave, shifted in frequency, travelling backward towards the detector. Some level of temporal instability and chaotic behavior in the backscattered intensity and in its spectral line shift will be observed in the fiber-ring. It is thus essential to know whether insertion of an amplifier in the fiber-ring will further destabilize the optical system. Since our proposed Brillouin-active fiber-ring sensor 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 detected signal will also be viewed on a Microcomputer for comparison.

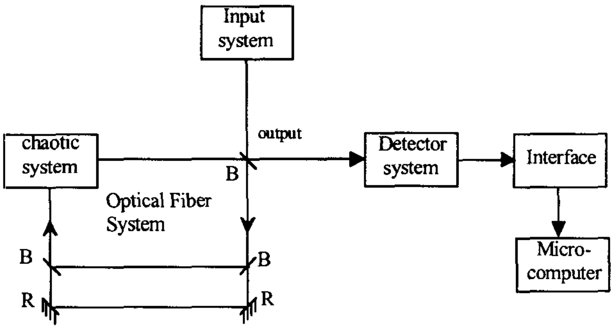

Fig.3. Experimental schemes for measuring chaos induced instabilities in optical fiber-ring sensor system. *R* is the mirror reflectivity and *B* is beam splitter.

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 4.

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 (100*μsec /division*), the Brillouin output exhibits randomly distributed trains of periodic pulses. Partial stabilization of amplitude fluctuations is achieved as laser pump power approaching maximum value. These experimental features are shown in time domain in Fig. 4 (a) through (f). At lower power, the Brillouin instability can occur at before threshold. This required power is much lower than normal Brillouin process intensity involving single pump power(see fig.4(a) and (b)). The temporal evolution immediately above threshold is periodic and at lower intensities can become chaotic(see fig. 4(c) and 4(d) at threshold level).

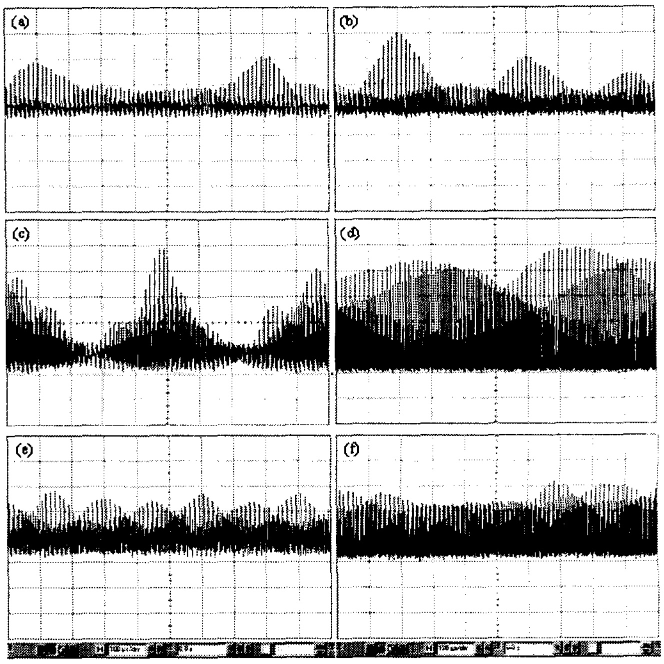

Fig.4. Temporal structures of Brillouin induced chaos and instability; (a) before threshold, (b) immediately before threshold, (c) at threshold, (d) immediately above threshold, (e) above threshold, (f) high above threshold.

On increasing the pump power towards above threshold(~14*mW*), the chaos induced instability that initiates this process is dramatically suppressed, giving rise to highly deterministic dynamics, or low dimensional chaos, evolving from quasi-periodicity(see fig.4(e)). It is shown experimentally that, fiber-ring feedback were suppressed in the amplification process of the Stokes wave, giving rise to deterministic behavior effect, the forms of which are found to be critically dependent on the strength of the nonlinear refraction in the Brillouin-active fiber-ring. On increasing the pump level to high above threshold(~16*mW*), the period of the regular modulation becomes shorter while other behavior remains essentially unchanged; that is, instability shows also periodical pulse of Brillouin emission showing it to be chaotic(see fig. 4(f)). Chaos induced instability is also periodic with much higher frequency content since fiber-ring sensor was equivalent to zero feedback. In the data, 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.

In the fiber-ring implemented threshold setup, the net gain of Stokes wave as a function of the equivalent pump power is shown in Fig. 5. It shows that changing of pump power is reflected as change in the 0*dB*(1.0) gain point. The threshold of the fiber-ring sensor can be controlled by changing the power launched in the Stokes wave. Thus different sensor wave can have different threshold. For a singlemode optical fiber with 1*km* length, the fact that threshold incident laser power required is on the order of 10 *mW*. Thus, the sensor power level should be 10 *mW*, and the pump power level should be greater than 10 *mW*. The intensity level of each wave is below the Brillouin threshold in order to avoid the generation of backward Stokes from spontaneous scattering. In this result, we see that the threshold for the Brillouin instability in fiber-ring is lower than the threshold for the normal Brillouin process.

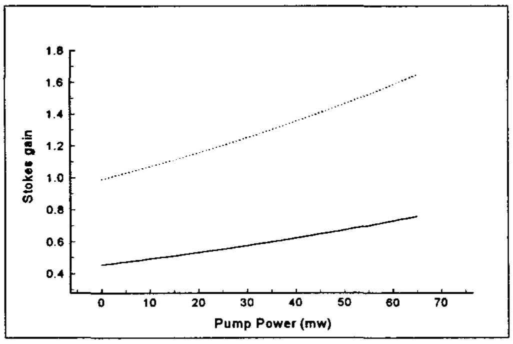

Fig.5. Net gain of backscattered Stokes wave versus as a pump power; gain in fiber-ring sensor(doted line) and fiber sensor(solid line) for comparison.

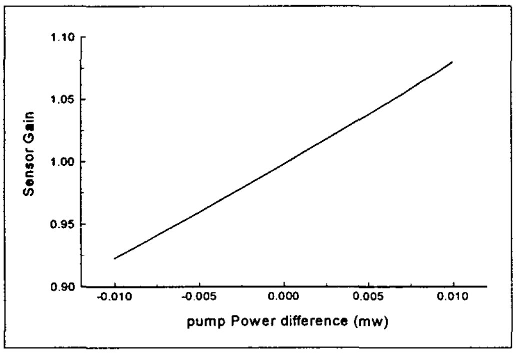

Fig.6. Backscattered Stokes wave versus pump power difference.

The Stokes gain *vs* versus total pump power difference is shown in Fig. 6. This figure shows that the sensor gain in fiber-ring can be converted to loss and vice versa, simply by changing the pump power levels. The output state of a sensor wave in fiber-ring can be changed by changing one or both input sensor intensities.

4. Conclusion

We have demonstrated that Brillouin scattered waves in a Brillouin-active fiber-ring sensor are temporally unstable above certain threshold intensity. It has been shown that for a variety of nonlinear interactions the chaos induced instability can become unstable in the form of growing temporal fluctuations and that under certain circumstances. We have also shown how the threshold for the onset of instability varies as a function of the ratio between the input signal intensities for various values of the Brillouin output. The Brillouin instability in fiber-ring can occur at a threshold intensity much lower than that normally required for Brillouin process. The temporal pulse train in threshold is periodic and at higher intensities can become chaotic. The Brillouin instability in fiber-ring sensor was considered for the case of an optical fiber with a Kerr nonlinearity having a noninstantaneous response in optical systems.

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