English

Research Express@NCKU Volume 5 Issue 7 - September 12, 2008
[http://research.ncku.edu.tw/re/articles/e/20080912/3.html]

Photonic microwave transmission using optically injected semiconductor lasers in period-one oscillation

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Optics Express 15 (22), 14921 (2007)

Microwave photonics has attracted much academic and practical attention over the past decade [1]. An important driving force behind the technology is the increasing demand for transmitting microwave subcarriers through optical fibers [2]. In such a radio-over-fiber (RoF) system, a central office is connected to remote base stations by optical fibers, where carrying microwave subcarriers are transmitted. At the base stations, photodetectors recover the microwave signals, which are then radiated to wireless customer units. RoF has the advantages of centralizing the high-speed electronics in the central office and allowing effective long-distance microwave transmission. However, most RoF systems are subject to the chromatic dispersion-induced microwave power penalty due to the double sideband (DSB) characteristic of the optical signals [3]. The problem can be avoided by using single sideband (SSB) modulation scheme. As a result, a number of SSB optical microwave sources have been developed, such as heterodyning two lasers, SSB electro-optic modulators, multi-section semiconductor lasers, and filtering directly modulated semiconductor lasers. However, these methods are usually limited in terms of microwave stability, optical efficiency, or frequency tunability.

In this study, we report on a RoF source based on a semiconductor laser subject to external optical injection. A schematic of the system setup is shown in Fig. 1. The output of the master laser is optically injected into a single-mode slave laser, and the output of the slave laser is sent to a detection system to monitor its optical and power spectra. The injection invokes the intrinsic nonlinear dynamics of the slave laser into period-one oscillation [4]. The oscillation causes a microwave modulation on the optical carrier. The system therefore becomes a photonic microwave source. This source is widely tunable far beyond the original bandwidth of the slave laser. A microwave frequency of up to 6 times the relaxation oscillation frequency of the slave laser can be achieved, which is higher than 60 GHz in our study. The system requires no lossy external modulation optics. The photonic microwave can also be stabilized using simple several microwave locking methods. By properly adjusting the injection conditions, the modulation can become nearly SSB to eliminate the chromatic dispersion-induced power penalty. Our observations show that the optically injected semiconductor laser in the period-one oscillation is an ideal candidate for RoF applications.

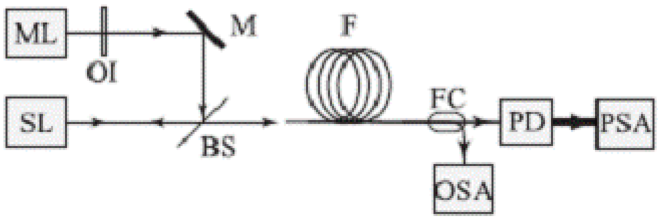

Fig. 1. Schematics of the system setup. ML: master laser; SL: slave laser; OI: optical isolator; M: mirror; BS: beam splitter; F: fiber; PD: photodiode; PSA: power spectrum analyzer; OSA: optical spectrum analyzer.

The optical spectra of two different period-one states are shown in Fig. 2. The optical frequency of the master laser, f_i , is kept at 20 GHz relative to the slave laser while the injection strength ξ_i is varied. Both spectra consist of the regeneration of the injected light at f_i and many sidebands separated by the period-one oscillation frequency f_0, or the microwave modulation frequency on the optical carrier, However, the relative magnitudes of these frequency components and f_0 change with the injection strength. When ξ_i = 0.065 as in Fig. 2(a), the principal component is at (f_i - f_0), where f_0 is about 20 GHz. It is surrounded by two sidebands at (f_i - 2f_0) and f_i, which are of similar magnitudes. This period-one state is regarded as nearly DSB because the magnitude difference between the upper and lower sideband is only about 3 dB. On the other hand, when ξ_i = 0.268 as in Fig. 2(b), the principal component is at f_i, which corresponds to the injected light, and f_0 is now about 30 GHz. It has two highly asymmetric sidebands. The lower sideband at (f_i - f_0) is more than 21 dB stronger than the upper sideband at (f_i + f_0). The period-one state is thus nearly SSB and is desirable for low power penalty RoF transmission. Therefore, depending on the injection conditions, a period-one oscillation state can have an output of either DSB or SSB, and can have a different period-one oscillation frequency f_0. Therefore, the injection conditions need to be optimized for RoF transmission, which will be further addressed in the following discussion.

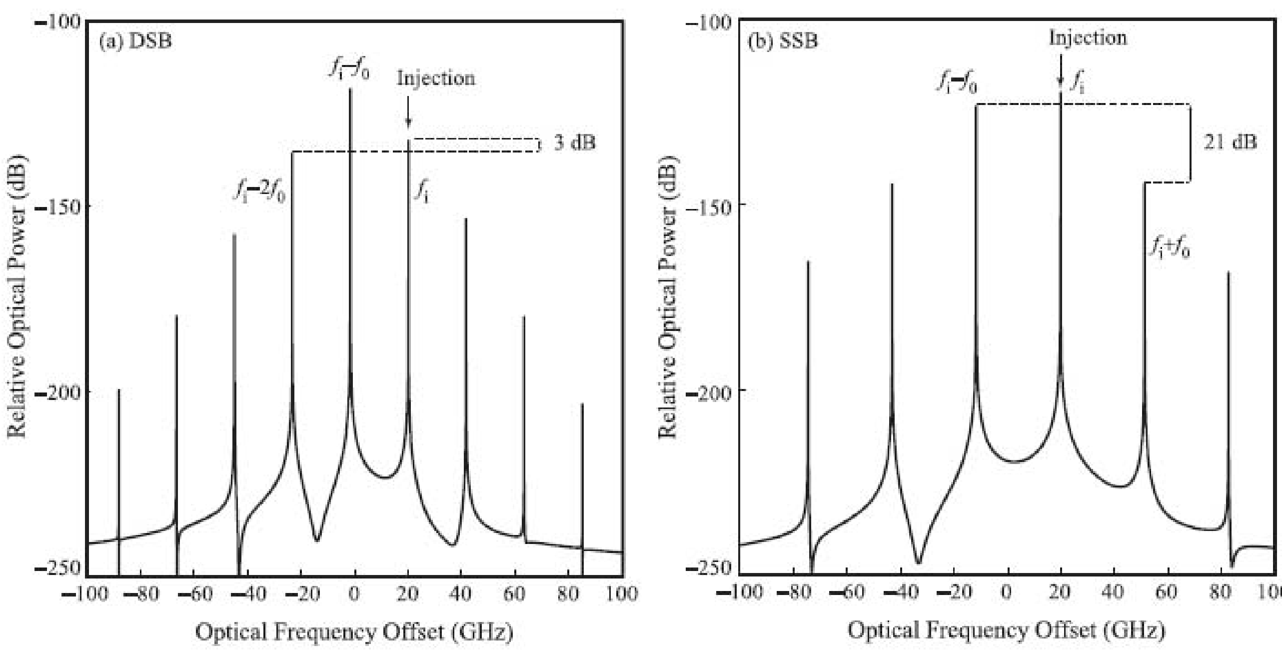

Fig. 2. Optical spectra of the slave laser in period-one states. (a) DSB period-one generated at (ξ_i, f_i) = (0.065, 20:GHz). (b) SSB period-one generated at (ξ_i, f_i) = (0.268, 20:GHz). The frequency axis is relative to the optical frequency of the slave laser.

The dependence of f_0 on ξ_i and f_i is more clearly presented as a contour map in Fig. 3. A large region of period-one oscillation is identified above the stable locking region across the Hopf bifurcation line. Period-two and chaotic regions are embedded within the period-one region. The contour lines of constant f_0 reveal that f_0 increases with ξ_i in nearly the whole period-one region. The optical injection system is capable of generating widely tunable microwave signals of over 60 GHz, which is almost 6 times the free-running relaxation resonance frequency of the laser. Even higher frequencies can be obtained by increasing f_i until f_0 reaches the free-spectral range of the laser, which is typically a few hundred gigahertz for an edge-emitting laser. Experimentally, period-one oscillation faster than 100 GHz has been observed in our system.

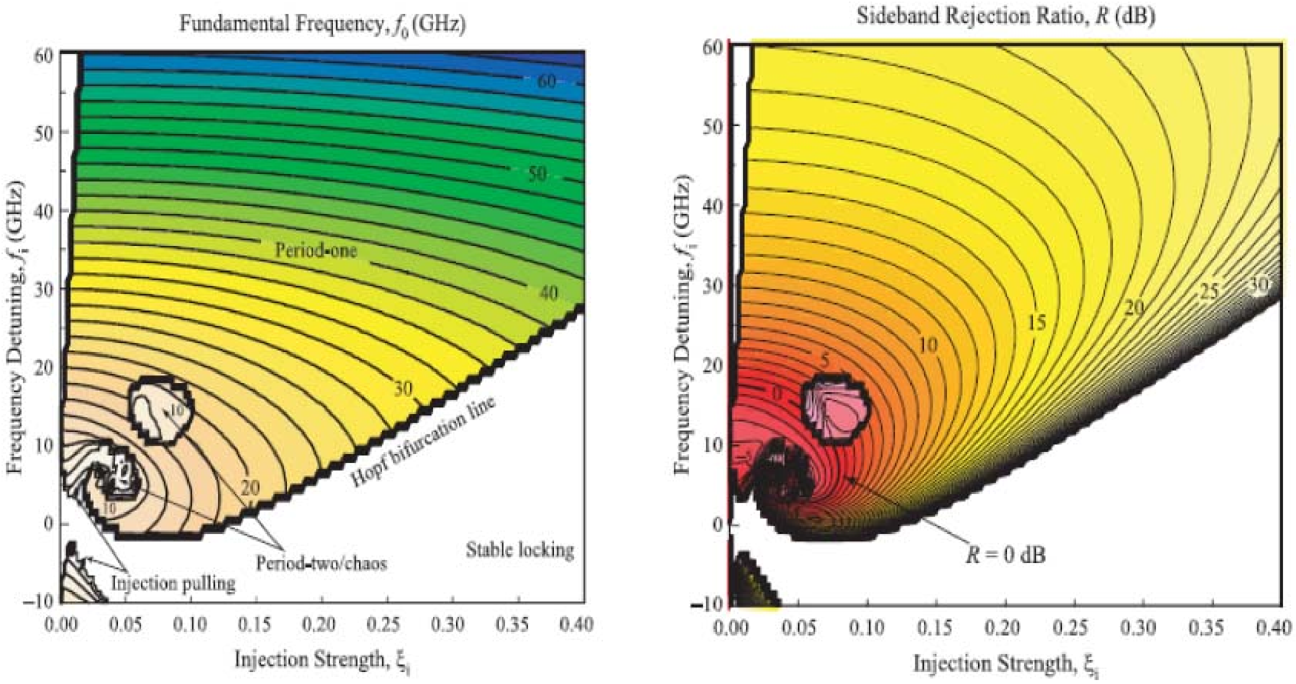

Fig. 3. Contour maps of the fundamental period-one frequency f_0 (left figure) and the sideband rejection ratio R (right figure).

Referring to the optical spectra in Fig. 2, our study shows that the period-one state consists mainly of a central carrier at (f_i - f_0), which is surrounded by the sidebands (f_i - 2f_0) and f_i. Other frequency components, including that at (f_i + f_0), are generally much weaker in intensity, and thus have negligible effects on the system. A true SSB would consist of only the components at (f_i - f_0) and f_i, whereas a balanced DSB has equal (f_i - 2f_0) and f_i. components. The SSB characteristics can be quantified by the sideband rejection ratio, R, which is defined here as the ratio between the intensity of f_i. component and that of (f_i - 2f_0) component. The dependence of R on ξ_i and f_i is also presented as a contour map in Fig. 3. Although the period-one oscillation is DSB along the 0-dB contour line, there is a large region of increasingly SSB states as the operation points moves away from the region enclosed by the 0-dB line. At the proximity of the Hopf bifurcation line, states with the f_i, component over 20 dB stronger than the (f_i - 2f_0) component can be easily found, which can be practically regarded as an SSB signal. It is desirable to operate the laser system in this region such that the dispersion-induced power penalty is minimized.

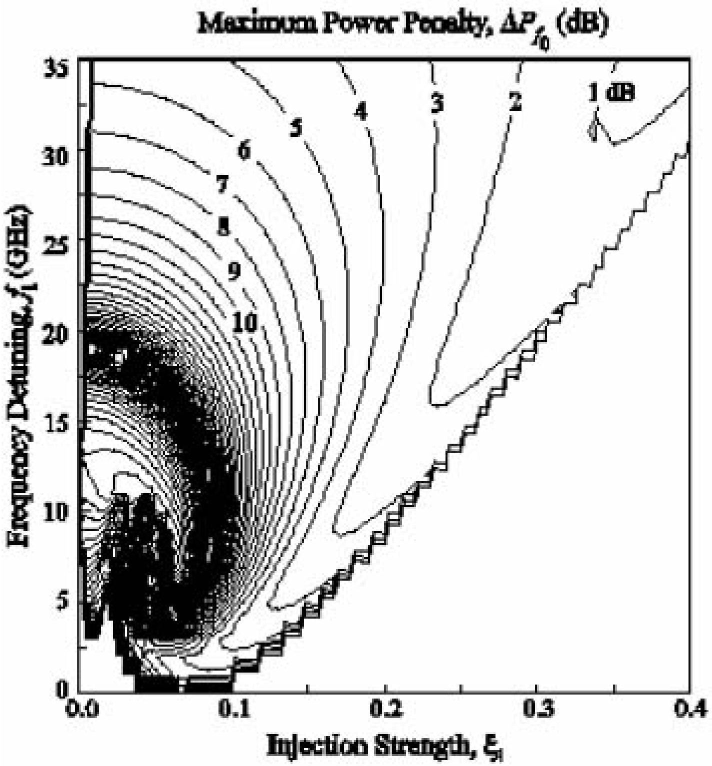

Fig. 4. Contour maps of the maximum power penalty after fiber propagation.

Figure 4 presents the power penalty performance as the maximum power variation for an arbitrary fiber length. The region slightly above the Hopf bifurcation line is shown to be most immune to the power penalty. It corresponds to the region of SSB period-one states in Fig. 3. Combining Figs. 3 and 4, we observe that the period-one state can be broadly tuned between f_0 = 22 and 62 GHz if a maximum power penalty of 3 dB can be tolerated. Therefore, the period-one state under properly adjusted injection is an ideal candidate for RoF applications that requires high immunity to power penalty.

In conclusion, the RoF performance of the period-one oscillation generated by an optically injected semiconductor laser is reported. The laser is shown to generate microwave frequency of up to 6 times its free-running relaxation resonance frequency. Over the wide tuning range of the generated frequency, the period-one state gives nearly constant microwave output power. Nearly SSB operation can be obtained over the broad tuning range. As a result, even with the worst case power penalty considered, the period-one state can be broadly tuned while keeping only a small variation in the output microwave power. The results suggest that the period-one state of the optically injected semiconductor laser is an attractive source for delivering microwave signals over fibers.

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