CHIN.PHYS.LETT. Vol. 25, No. 11 (2008) 3980

Phase Noise of Optically Generated Microwave Using Sideband Injection Locking *

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(Received 17 June 2008)

Optically generated 20-GHz microwave carriers with phase noise lower than −75 dBc/Hz at 10 kHz offset and lower than −90 dBc/Hz at 100 kHz offset are obtained using single- and double-sideband injection locking. Within the locking range, the effect of sideband injection locking can be regarded as narrow-band amplification of the modulation sidebands. Increasing the current of slave laser will increase the power of beat signal and reduce the phase noise to a certain extent. Double-sideband injection locking can increase the power of the generated microwave carrier while keeping the phase noise at a low level. It is also revealed that partially destruction of coherence between the two beating lights in the course of sideband injection locking would impair the phase noise performance.

PACS: 42.55.−f, 42.55.Px

Millimetre-wave (mm-wave) wireless communication is known to have several advantages, such as wide bandwidth, reuse of frequency band, good confidentiality and so on. However, generation and processing of mm-wave by electrical means is generally too costly to be feasible.[1] In recent years, optical generation and transmission of mm-wave signal for future broadband wireless communication systems have been extensively investigated. Optical technology can reduce the system cost and the transmission loss, and it can also offer immunity to electromagnetic interference.[2−4] At present, several optical techniques have been proposed to generate mm-wave carriers, including sideband injection locking,[5,6] mode-locked lasers,[7] optical phase locking ring[8] and external modulation.[9,10]

Among the various methods proposed so far, sideband injection locking is able to generate microwave carriers with high spectral purity and the system based on it has demonstrated high stability and tunability for the carriers.[11] Meanwhile, sideband injection locking offers the potential to fabricate monolithic integrated devices for rf carrier generation.[12] In such applications, phase noise is often used to characterize the quality of the generated microwave carrier. How to control the phase noise of the beat signal is a key problem in optical microwave generation by sideband injection locking.

In this Letter, single- and double-sideband injection locking is used to generate microwave carrier at the frequency of 20 GHz. Phase noise characteristics of the generated microwave is investigated, and factors that affect the phase noise performance are analysed.

Firstly, microwave generation by single-sideband injection locking is investigated. Figure 1 shows the schematic diagram of the experimental setup. A Santec TSL-210V tunable laser acts as the master laser (ML), and its output is modulated by a $LiNbO_3$ modulator biased at its half-wave voltage V_π to suppress the optical carrier and to maximize the modulation sidebands. The modulated light is injected into the slave laser (SL) by way of a circulator. The SL is a commercial distributed feedback (DFB) laser without isolator, and its temperature is stabilized by an ILX Lightwave diode laser controller. The light coming out of the circulator is sent into a high-speed photodetector (PD) and the microwave beat signal is recorded by an electric spectrum analyser (ESA). Meanwhile, the spectrum of the light is monitored by an optical spectrum analyser (OSA).

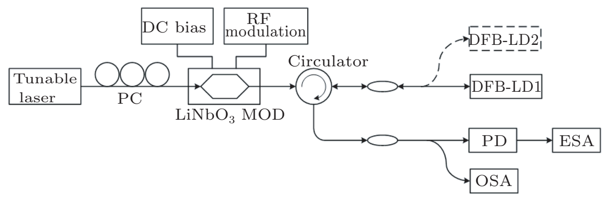

Fig. 1. Schematic diagram of single- and double-sideband injection locking. (PC: polarization controller; DC: direct current; RF: radio frequency; MOD: modulator; DFB-LD: distributed feedback laser diode; OSA: optical spectrum analyser; PD: photodetector; ESA: electric spectrum analyser).

In this experiment, the output optical power of the ML is set to −15 dBm, and the modulation frequency is at 10.0 GHz. The ±1st order modulation sidebands

*Supported by the National Natural Science Foundation of China under Grant Nos 60536020 and 50706022, the Major State Basic Research Project of China under Grant Nos 2006CB302800 and 2006CB921106, the High-Technology Research and Development Programme of China under Grant Nos 2006AA03A105 and 2007AA05Z429.
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due to the amplitude modulation will show up on either side of the optical carrier in the spectrum of the light exiting the $LiNbO_3$ modulator. The current of the SL is set to be 29.0 mA and its output power is about 0 dBm. The wavelength of the ML is fine tuned so that the SL is locked to the +1st order sideband. The output optical spectrum measured by the OSA is shown in Fig. 2(a). As the phase of the SL, which is locked to the +1st order sideband, is correlated to that of the −1st order sideband, 20-GHz microwave beat signal with high stability and purity can be observed with the ESA, as shown in Fig. 2(b). The power of the 20-GHz beat signal is −44.64 dBm and the 3-dB-down linewidth is less than 3 Hz. The measured phase noise of the 20-GHz microwave carrier is shown in Fig. 3, which indicates a phase noise of −86.6 dBc/Hz at 10 kHz offset and −92.8 dBc/Hz at 100 kHz offset from the carrier. As the microwave carrier generated by single-sideband injection locking is relatively weak, the phase noise at frequency offset over 100 kHz from the carrier is obscured by the noise floor of the ESA. In addition, a spike in the phase noise is observed at about 1 kHz offset.

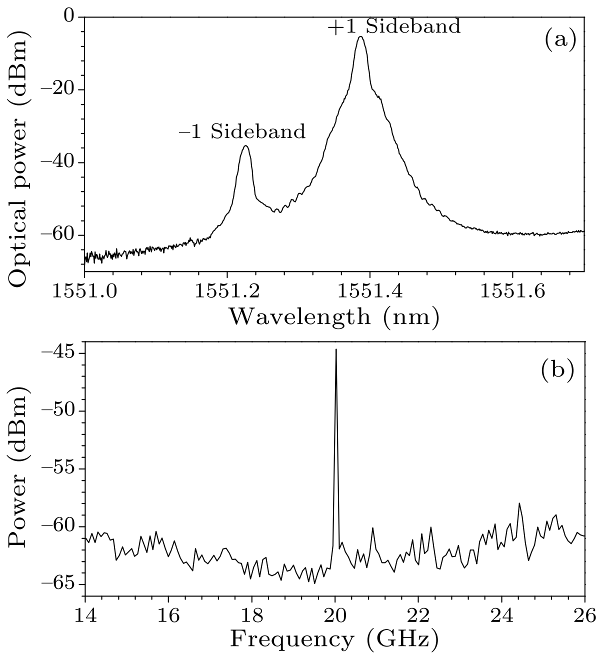

Fig. 2. Injection locking of the SL by the +1st order modulation sideband of the ML: (a) Optical spectrum displayed in the OSA, (b) electric spectrum of the generated 20-GHz microwave carrier.

We have also compared the power and the phase noise of the 20-GHz microwave signal obtained with different SL currents. Stable locking is verified when the SL current varies from 25 to 33 mA. The power of the 20-GHz beat signal increases from −47.87 and −42.46 dBm when the SL current is raised from 25.0 to 33.0 mA. The phase noise spectra of the 20-GHz microwave at different SL currents are shown in Fig. 3. It is seen that as the power of the beat signal increases, the phase noise at 10 kHz offset remains around −87 dBc/Hz. However, there is a clear improvement for phase noise at over 10 kHz offset. This is mainly due to the increase of the 20-GHz carrier power. The phase noise between 10 and 100 kHz offset is now raised above the noise floor, while the increased beat signal power results in a reduced noise-floor to carrier-power ratio for frequency offset over 100 kHz.

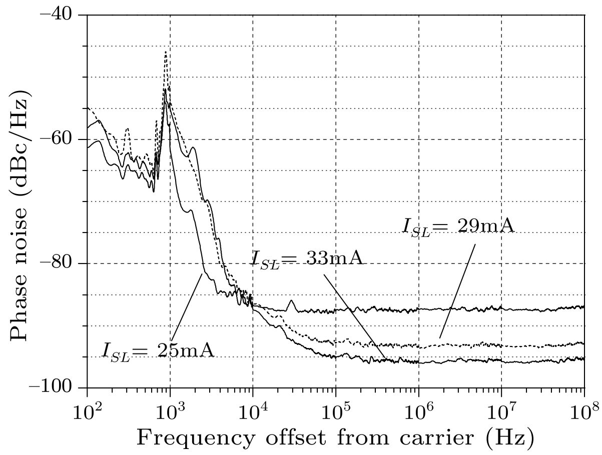

Fig. 3. Phase noise spectra of the 20-GHz microwave carrier generated by single-sideband injection locking at different SL currents.

Secondly, optical generation of microwave carrier by double-sideband injection locking is carried out. In this case, an additional DFB laser is used as the second SL as indicated by the dashed line in Fig. 1. To facilitate double-sideband injection locking, the wavelength of the second SL is chosen to be within 0.5 nm from that of the first SL. Again, an ML output power of −15 dBm is used. To realize simultaneous locking of the two SLs by the ±1st order modulation sidebands, the wavelengths of the SLs are fine tuned by adjusting their current and the temperature. When double-sideband locking is secured, the current of the SLs are around 29 mA, and the corresponding output optical spectrum is shown in Fig. 4(a). Compared with the case of single-sideband injection locking, a significant increase in the beat signal power can be obtained with double-sideband injection locking. As shown in Fig. 4(b), the power of the 20-GHz microwave carrier is as high as −24.40 dBm, with a 3-dB-down linewidth less than 3 Hz. The phase noise is measured to be −79.1 dBc/Hz at 10 kHz offset and −93.3 dBc/Hz at 100 kHz offset, as shown Fig. 5. Because of the increasing carrier power, the details of phase noise at frequency offset below 1 MHz are clearly revealed. For comparison, the phase noise spectrum of 20-GHz microwave signal generated by directly beating the two sidebands of the modulated ML is also plotted in Fig. 5. As the optical power of the ML is only −15 dBm, the beat signal is only −58.07 dBm and the phase noise above 1 kHz offset is masked by the noise floor of the ESA. By locking the SLs to the modulation sidebands, the power of the microwave beat signal can be significantly increased while maintaining a low phase noise level. In this sense, the effect of injection locking can be viewed as narrow-band amplification of the modulation sidebands within the locking range. It is more efficient than amplifying the ML output with a broadband optical amplifier such as erbium doped fibre amplifier (EDFA) or semiconductor optical amplifier (SOA).

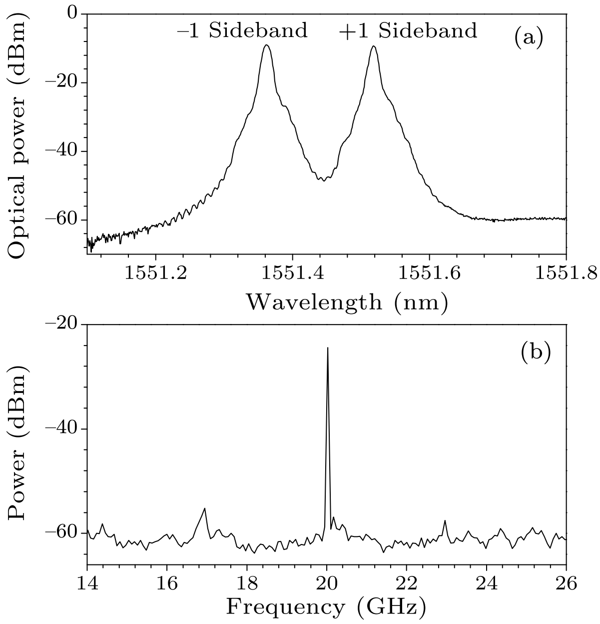

Fig. 4. Double-sideband injection locking of the SLs by the ±1st order sidebands of the modulated ML: (a) Optical spectrum displayed in the OSA, (b) electric spectrum of the generated 20-GHz microwave carrier.

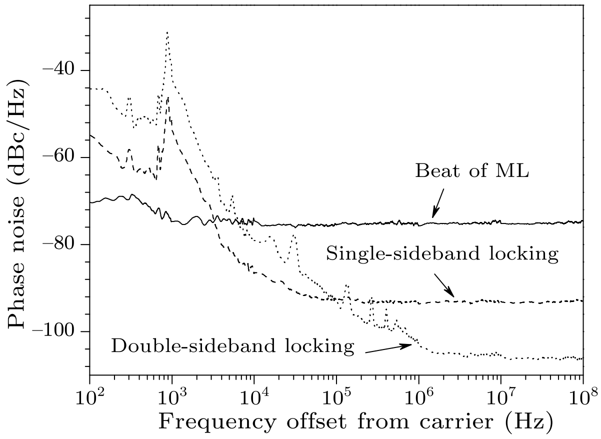

Fig. 5. Phase noise spectra of 20-GHz microwave generated by single-sideband injection locking, double-sideband injection locking and directly beat of the modulated ML.

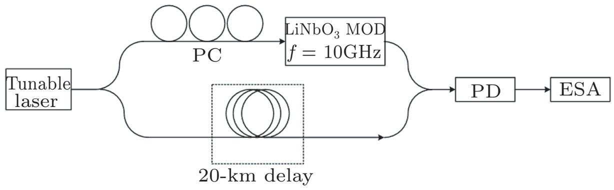

Fig. 6. Schematic diagram of the delayed self-heterodyne setup for linewidth measurement.

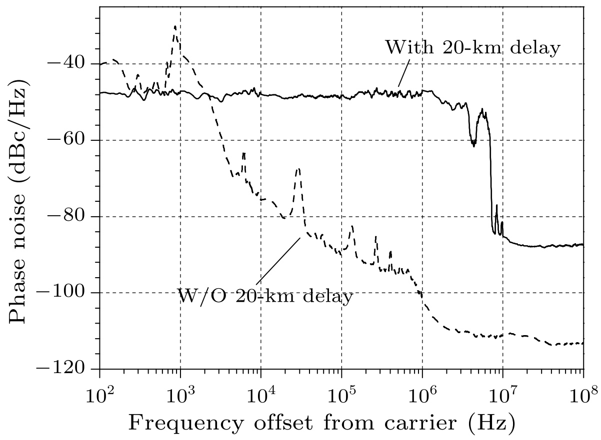

Fig. 7. Phase noise spectra of the 10-GHz beat signal with and without 20-km delay fibre.

Similar to the case of single-sideband injection locking, there are a series of peaks in the phase noise spectrum of the microwave carrier generated by double-sideband injection locking. It is considered to be related to destruction of coherence during the course of injection locking. To investigate the influence of the coherence between the beating lights on the phase noise of the microwave beat signal, the linewidth of the ML is measured by means of delayed self-heterodyne.[13] The test setup is shown in Fig. 6, where the output of the tunable laser is split into two paths by a fibre coupler. One path is modulated by a $LiNbO_3$ modulator with a modulation frequency of 10.0 GHz. The other path goes through a 20-km fibre delay to completely remove the coherence between the two paths. An ESA connected to a high-speed PD is used to analyse the lineshape of the 10 GHz beat signal between the modulation sidebands and the delayed light. The phase noise spectrum of the 10-GHz beat signal is shown in Fig. 7. As the tunable laser is an external cavity laser using a diffraction grating for wavelength tuning, its phase noise is almost constant for frequency offset lower than 1 MHz and its linewidth is about 3.5 MHz. On the other hand, if the 20-km fibre delay is removed, the coherence between the two beating lights is partially destructed due to the small difference in fibre length between the two paths. The corresponding phase noise of the 10-GHz beat signal is also shown in Fig. 7. A series of peaks arises in the phase noise spectrum and their positions are in good agreement with the case of sideband injection locking.

Therefore, it is believed that sideband injection locking causes partial destruction of coherence between the two beating lights, which gives rise to the peaks in the phase noise spectrum of the generated microwave. In the experiment of double-sideband injection locking, there is about 80-cm difference in the length of the two SLs' pigtail fibres, which would result in the partial destruction of coherence between the two beating lights. This is why the phase noise at low frequency offset is higher in the case of double-sideband injection locking. In future application of mm-wave generation by double-sideband injection locking, such partial destruction of coherence can be avoided by adopting a variable fibre delay line or by monolithic integration of the two SLs with a Y-branch coupler on the same InP substrate.

In summary, optical generation of microwave signal by single- and double-sideband injection locking has been investigated. We obtain 20-GHz microwave carrier with a phase noise lower than −75 dBc/Hz at 10 kHz offset and lower than −90 dBc/Hz at 100 kHz offset. It is demonstrated that the effect of sideband injection locking is similar to narrow-band amplification of the modulation sidebands. Meanwhile, the influence of the coherence between the two sidebands on the phase noise of the microwave beat signal is also investigated. It is found that partial destruction of coherence during sideband injection locking tends to deteriorate the phase noise of the generated microwave.

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