Noise Limit on the Accuracy of Frequency Locking of Lasers for Ultra-acurate Fiber-optic Time Transfer

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***Summary*—In the paper we discuss the frequency error occurring when synchronizing two semiconductor lasers under the conditions when the optical power of the reference laser is relatively weak (usually below minus thirty some dBm). This synchronization approach is intended to be used in ultra-accurate long-distance fiber optic time transfer links, which require accurate and stable frequency offset between the lasers used to convey the timing information between the terminals of the transfer system. We identified that the problem is caused by the noise (and resulting insufficient signal to noise ratio) at the input of a high-frequency prescaler forming a part of the signal processing chain. To understand undergoing processes we developed a Simulink/Matlab simulation model, supported by a theoretical approach that can help designing the laser frequency synchronization circuits for the fiber optic time transfer systems.**

Keywords—fiber optic, time transfer, laser frequency synchronization, frequency error, signal to noise ratio.

I. Introduction

In a typical fiber optic stabilized time transfer link, two lasers operating over the same fiber in opposite directions, are required. In long (>50 km) bi-directional time transfer links the noise caused by the Rayleigh backscattering requires an offset between the lasers' frequencies to allow filtering this undesired signal out in an optical domain. This creates asymmetry of the delays in the two propagation directions because of the fiber's chromatic dispersion.

For an ultra-accurate fiber optic time transfer the uncertainty contribution due to the abovementioned asymmetry starts to be a limiting factor determining transfer accuracy. To reduce this contribution to acceptable level the relative stability and accuracy of used lasers is a crucial parameter [1].

Stability of lasers wavelengths can be obtained either with individual wavelength references (e.g. so-called wavelength lockers based on Fabry-Perot etalon) or by frequency locking one of the lasers to the other one. This second approach allows obtaining much better accuracy of the lasers relative frequency, resulting in substantially lower uncertainty contribution due to the chromatic dispersion (at the order of single picoseconds and almost independent on the link length) [2].

Nowadays, thanks to relatively easy access to various millimeter wave electronic components, like amplifiers, mixers, frequency multipliers, frequency synthesizers and high speed frequency dividers, as well as high-speed photodiodes, the offset between the lasers reaching even 50 GHz can be obtained. In practice, the offset must comply with the frequency grid used in dense wavelength division multiplex (DWDM) fiber optic systems as using the DWDM optical filters is the only option available at a reasonable cost.

II. Methods/Results

The general idea of the proposed circuit is shown in Fig. 1. It comprises a semiconductor laser (either a simply current-controlled distributed feedback (DFB) or an integrable tunable laser assembly (iTLA)), whose frequency ν_S is controlled in a way to get a constant, predetermined frequency offset with respect to the reference laser ν_{REF}. The value of this offset is determined by the local oscillator frequency f_{LO} (set by a microwave synthesizer) and selected intermediate frequency f_{IF}. The steering signal is obtained by beating the fields of the two involved lasers using a high-speed photodiode. The resulting beat note, being a microwave signal in the range between 12.5 GHz and 50 GHz (depending on the required

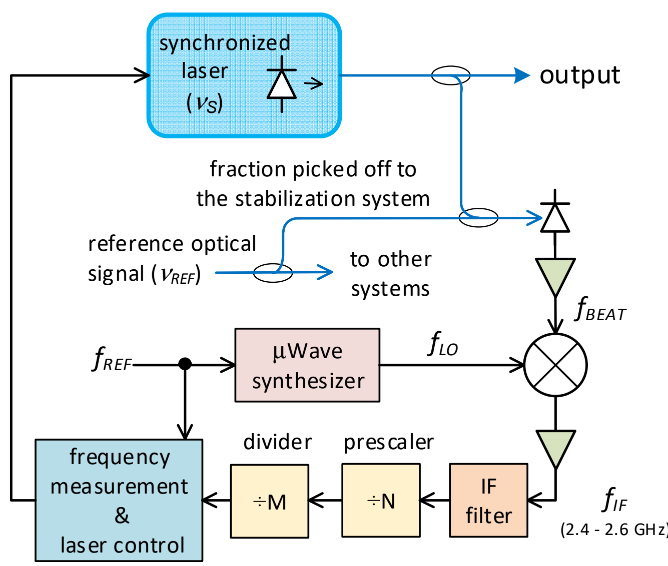

Fig. 1. Generic block diagram of the circuit for the frequency synchronization of a semiconductor laser to the reference optical frequency with a defined frequency offset.

frequency offset between the lasers) is further processed by a chain composed of amplifiers, mixers and dividers to get the signal with the frequency low enough to be conveniently measured (5 MHz in our case). The frequency measurement is then done by a timer, which is a piece of hardware available on any standard microcontroller and assures enough accuracy in considered application [2]. Depending on the sign of the gain set in the feedback loop, the frequency offset between the lasers ν_S - ν_{REF} can be either positive or negative, and its absolute value corresponds to the beat note frequency:

$$f_{BEAT} = |\nu_S - \nu_{REF}| = \\ = N \cdot M \cdot f_{REF} + f_{LO} = (N \cdot M + K) \cdot f_{REF}, \quad (1)$$

where f_{REF} is the frequency of an electrical oscillator supplying the reference for the microwave synthesizer and the timer measuring the divided f_{IF} frequency. N and M are the division ratios of the prescaler and the subsequent divider respectively, and K is the multiplication factor of the microwave synthesizer.

In proposed circuit the difference between the assumed and measured values of the frequency offset between the lasers (i.e. the frequency offset error) is expected to be small, depending mainly on the accuracy of the f_{REF} oscillator. Using a standard temperature compensated crystal oscillator (TCXO) the accuracy in the order of tens of kHz should easily be realized, which is enough to make the contribution of lasers' frequency accuracy negligible, even for 1000 km long time transfer links [2, 3].

To confirm our predictions a few prototypes working on the principle described above have been built, with offsets equal to 12.5 GHz, 25 GHz and 50 GHz. It was observed during the prototypes evaluation, however, that when the power of the reference optical signal is reduced to some low level (in the range between -40 dBm to -35 dBm, depending on the details of the specific circuit realization), a substantial error occurs, which can make the offset frequency differing by even a dozens of MHz from its required value. It is important to note here that the laser stabilization circuit is a subsidiary subsystem and must operate reliably with low optical powers, as the reference signal can be only a fraction of the available reference optical power. Having this in mind the recognition, understanding and keeping under control any possible frequency errors is important.

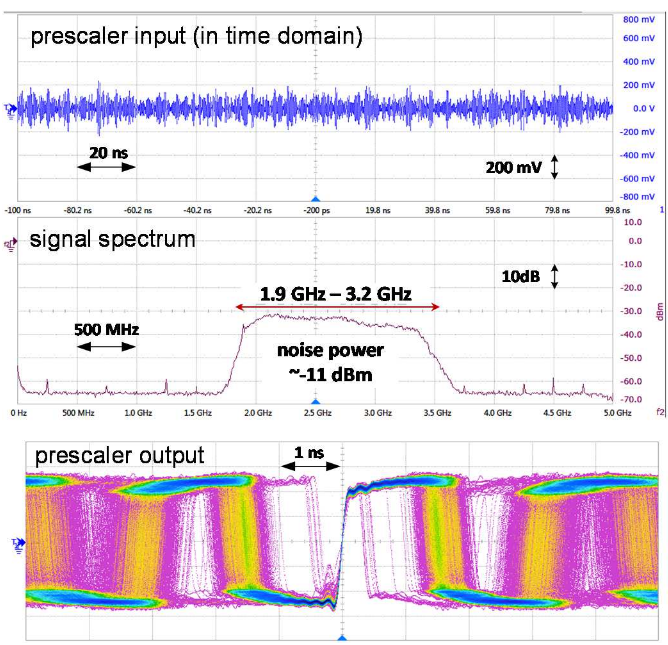

Fig. 2. Noise at the prescaler input in a frequency synchronization circuit with the offset of 12.5 GHz with the optical reference removed. The lowermost picture shows the waveform at the prescaler output.

Careful examination of the prototypes built revealed, that the high-frequency prescaler, dividing the f_{IF} frequency by N ($N = 8$ in our case) is a source of the observed problem. To understand this behavior we started from investigating the operation of a prescaler driven by a low-level signal. It is a well-known fact that the prescaler self-oscillates with no signal applied to its input [4]. In our case the situation is different, however, as quite substantial noise (see example in Fig. 2), coming from the resistor terminating the photodiode and from the shot noise of impinging light, drives the prescaler. Theoretical analysis using a level-crossing approach [5] shows that under such conditions the mean number of crossings in a time interval (which can be called a mean frequency) takes a well-defined value, which, when knowing the power spectrum of the noise $S(f)$, can be expressed as:

$$f_M = \int_{-\infty}^{+\infty} f^2 \cdot S(f)\, df \Big/ \int_{-\infty}^{+\infty} S(f)\, df \,. \quad (2)$$

For a uniform, band-pass noise centered around f_0 the above formula simplifies to:

$$f_M = \sqrt{f_0^2 + f_C^2/3}\,, \quad (3)$$

where $2f_C$ is the width of the noise spectrum. In the lowermost part of Fig. 2 the output of the prescaler driven by the noise is shown. The measured frequency is equal to 317.23 MHz, which gives 2537.84 MHz after multiplying by 8 and corresponds quite well with the value f_M = 2577.47 MHz obtained from (3). The prescaler used was HMC988 from Hittite/Analog Devices.

No useful formulas, however, are known to the authors allowing estimating the mean frequency of the crossings when a sinusoidal component is added to the noise. To obtain some estimation a simulation model build using the Simulink/Matlab software was used, where the random process at the prescaler input was modeled as a sum of a sinusoid and a uniform, bandpass Gaussian noise (see Fig. 3).

Example results of the simulations (in both linear and logarithmic scales) are shown in Fig. 4 for a few values of the f_{IF} to f_M ratios. Using developed tools we found that the value of the offset frequency error (shown in the graphs as a difference between the measured f_{meas} and desired f_{IF} frequencies, referenced to f_{IF}) is closely related to the signal to noise ratio (SNR) at the input of the prescaler. Moreover, the

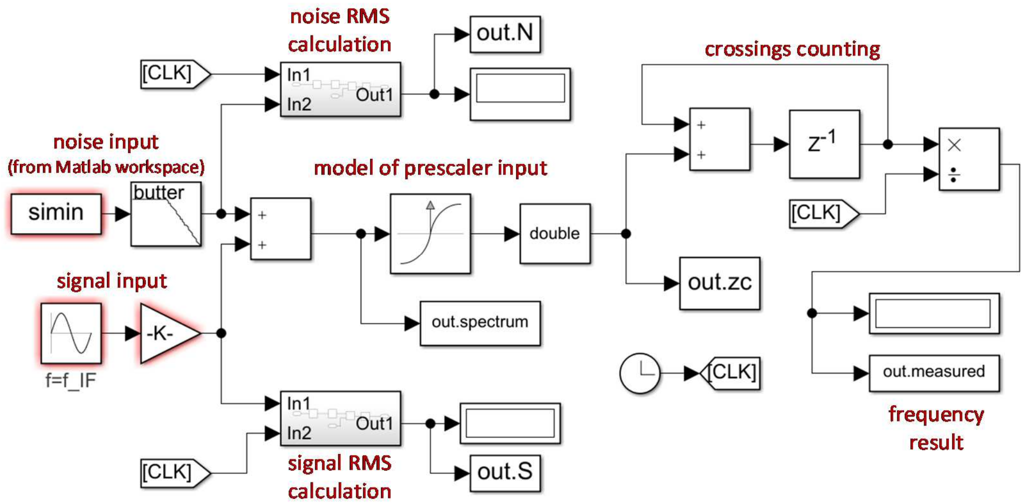

Fig. 3. Simulink model used to estimate the frequency counted by the prescaler.

sign of the error can be either negative or positive, depending on the relation between the f_{IF} and f_M frequencies. For very low values of the SNR (i.e. almost no sinusoidal component), the value of f_{meas} approaches f_M and the offset error is maximal. Its value can be really huge (blue and green curves), reaching tens of MHz for f_{IF} around 2.5 GHz. When the f_{IF} close to f_M is chosen, however, the error can be reduced substantially (red curve). In any case the error diminishes rapidly when SNR is increased, and drops to below 10^{-5} for the SNR exceeding some 10 dB or 12 dB. For the f_{IF} around 2.5 GHz this corresponds to the absolute error in the range of some dozens of kHz, which is perfectly adequate in

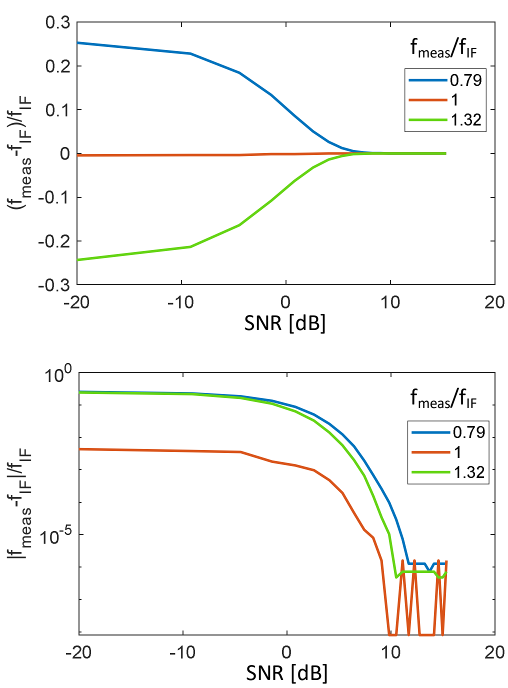

Fig. 4. Simulation results showing the relative offset frequency error versus the signal to noise ratio, plotted in the linear (upper plot) and logarithmic scales (lower plot).

considered applications of ultra-accurate fiber optic time transfer. The floor visible in the logarithmic plot (the lower part of Fig. 4) results from limiting the number of simulated data points to 2^{22} to make the simulation time reasonable.

III. Prescaler Selection

Another important problem, which we encountered in our research, is proper selection of the prescaler to assure the reliable operation of the entire circuit. We tested a few divide-by-eight or programmable prescalers from Hittite/Analog Devices, with rated frequency of operation ranging from 4 GHz up to 24 GHz (HMC988, HMC705, HMC363, HMC494 and HMC862A) and determined that not all of them can perform equally well.

The sensitivity of the prescaler, which for most commercial devices is usually better than -15 dBm, does not seem to matter much in considered application as the device input contains substantial level of noise, preventing its self-oscillation. The maximum frequency of operation, on the other hand, appears to be critical as a high-speed prescaler is able to produce short glitches at its output when driven by a noisy input. This can be harmful for the next divider stage. Such a situation is shown in Fig. 5, where the reaction of a LMK0200 800 MHz programmable divider to a 250 ps long glitch

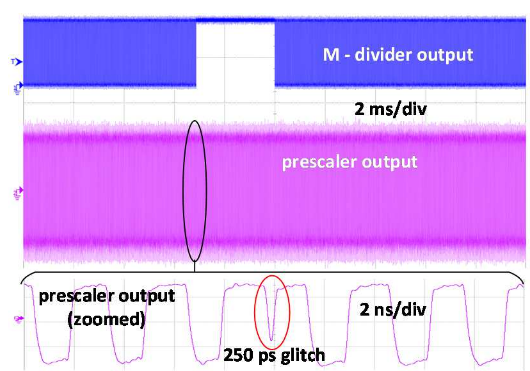

Fig. 5. Response of LMK0200 programmable divider to a short glitch at its input.

produced at the output of a HMC363 prescaler (rated for 12 GHz) is shown. One can notice that the operation of the M-divider can be seriously affected by such a glitch, resulting in blocking its output for about 3 ms (whereas the nominal frequency of the divider equals to 2.5 MHz). As the origin of such a behavior has not been understood or explained, it was determined empirically that from the tested prescalers the only one that performed satisfactory (i.e. with no any evidence of interrupting the operation of the M-divider) was HMC988, rated for 4.5 GHz.

IV. Conclusions

The frequency error identified in our research can become an important contribution affecting the time transfer accuracy, so understanding this problem is important when considering ultra-accurate fiber optic time transfer. Although the problem requires further research to fully understand the resulting limitations the theoretical model we developed can predict the general behavior of the phenomenon and can be used to help designing the laser synchronization circuits.

The problem of the observed frequency error at low signal levels can be circumvented by, e.g., preceding the prescaler with a PLL-based tracking filter, which will strip-off the noise and stabilize the amplitude of the IF signal. This will result, however, in the serious increase of the system complexity. Another, quite simple and effective solution can be setting the f_{IF} frequency to coincide with f_M that can simply be done by proper adjustment of the microwave synthesizer multiplication factor.

The problem with blocking the operation of the M-divider by short glitches produced at the prescaler's requires placing special attention on selecting appropriate device to be used in circuits for laser synchronization utilizing the idea underlined in this paper.

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