MenloSystems

Ultrastable Microwaves

Dividing phase noise. Shifting paradigms.

Ultrastable microwave systems use optical frequency division to precisely scale optical frequencies down to the microwave and RF range. The technique dramatically reduces RF phase noise to levels once thought unattainable - marking a paradigm shift in RF signal synthesis. This primer breaks down the key ideas behind the technology.

Optical Frequency Combs

Simply put, an optical frequency comb is a special type of laser that produces a spectrum of equally spaced light frequencies, resembling the teeth of a comb in frequency domain - hence the name. Optical frequency combs can be produced by ultrashort pulsed, mode-locked lasers (Fig. 1)
Mode-locking is a form of self-organization among the longitudinal laser cavity modes into an ultrashort pulse, ensuring equal frequency spacing and phase synchronization between individual modes. The pulse circulates within the laser resonator at a specific repetition rate f_{rep}, set by the round-trip time of pulse propagation along the cavity resonator length. The laser output - a train of ultrashort pulses in the time domain - is generated by transmitting copies of this circulating pulse through a partially transmissive end-mirror of the cavity. Note that due to dispersion within the laser cavity, a mismatch between group and phase velocity occurs, translating into a gradual slip ($\Delta\phi$) of the carrier wave relative to the pulse envelope. This is known as the carrier-envelope phase offset (Fig. 1, bottom left).

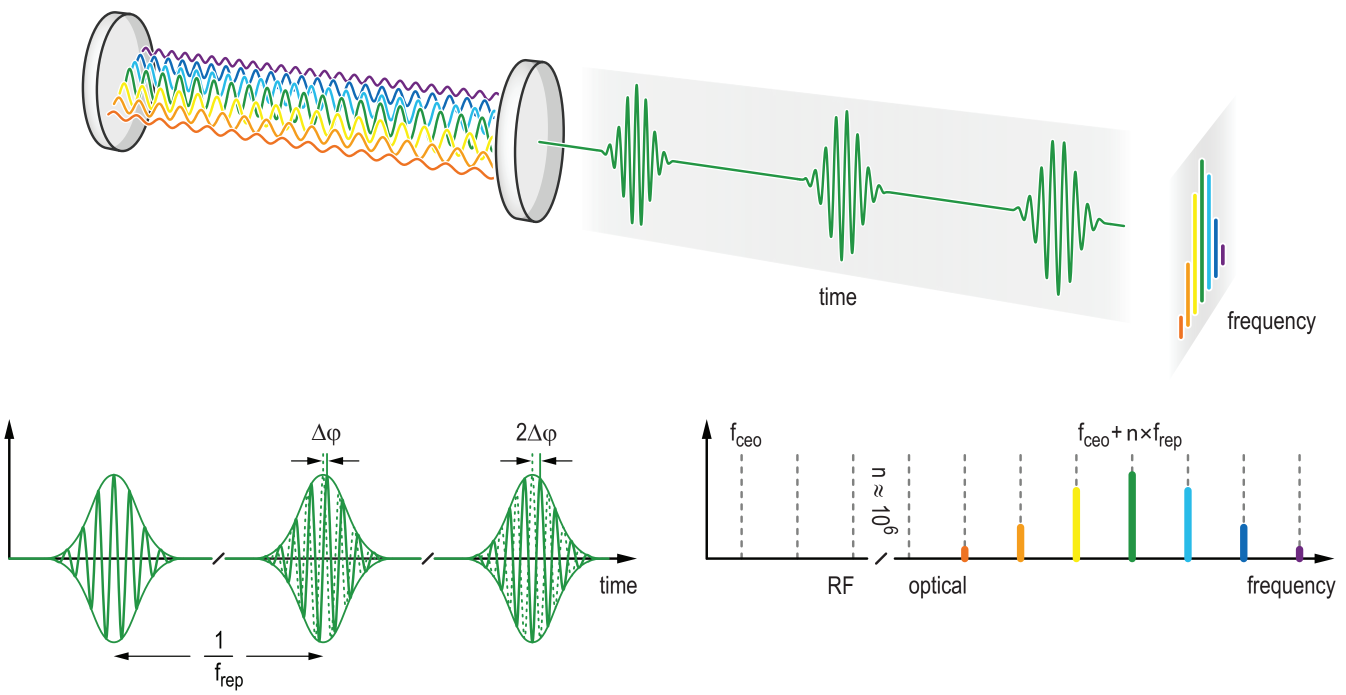

Figure 1. *(Top) Optical frequency comb produced by an ultrashort pulsed, mode-locked laser. (Bottom) A periodic pulse train in the time domain (left) corresponds to a series of discrete frequencies in the frequency domain (right). The frequency comb is offset by a certain amount f_{ceo} (a consequence of the pulse-to-pulse carrier envelope phase slip $\Delta\phi$), but otherwise entirely composed of equally spaced frequencies that are separated by the repetition rate f_{rep} .*

In the ideal case (i.e. in the absence of any perturbations) the Fourier relationship between the time and frequency domains dictates that a periodic pulse train in time corresponds to a series of discrete frequency modes (Fig. 1, bottom right). In the frequency domain, the frequencies of the comb are given by

$$\nu_n = f_{ceo} + n\, f_{rep}$$

where ν_n is the optical frequency of the n-th comb line, f_{ceo} is the carrier-envelope offset frequency, n is an integer index, and f_{rep} is the repetition rate of the laser. In other words, the frequency comb is offset by a certain amount f_{ceo} (a consequence of the pulse-to-pulse carrier-envelope phase slip), but otherwise entirely composed of equally spaced frequencies that are separated by the repetition rate f_{rep}.
The above equation is nothing short of a landmark achievement, as it establishes a direct link between an optical frequency (ν_n) and two RF frequencies (f_{ceo} and f_{rep}). Accordingly, in a mode akin to a reduction gear, frequency combs can be used to divide optical frequencies down to the RF domain.

OPTICAL FREQUENCY DIVISION

As illustrated in Fig. 2, optical frequency division begins by locking an optical frequency comb in two degrees of freedom, effectively anchoring the comb spectrum at both ends.
The first degree of freedom involves locking the carrier-envelope offset frequency (f_{ceo}), to stabilize the lowest-frequency comb tooth (Fig. 2 / ❶). Notably, measuring and stabilizing f_{ceo} , also known as self-referencing, posed a significant challenge in the early development of optical frequency combs. The advent of octave-spanning frequency combs - those covering a frequency range more than twice the lowest frequency - has enabled a simple yet efficient implementation (commonly referred to as the “f-2f” method).
With the lowest-frequency comb tooth pinned, the second degree of freedom is addressed through an “optical lock” of one of the optical comb teeth (ν_n) to an external optical reference frequency ν_{cw} (Fig. 2 / ❷).

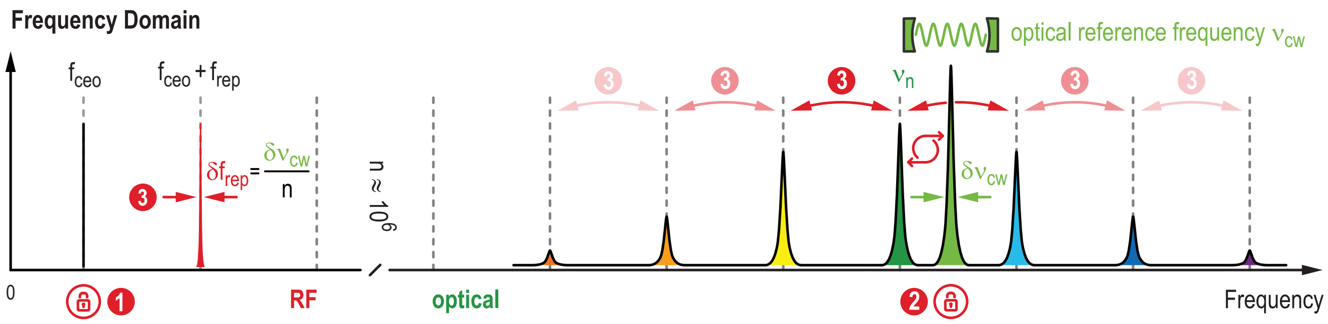

Figure 2. *Frequency domain perspective of optical frequency division.* ❶ *Locking the carrier-envelope offset frequency (f_{ceo}) stabilizes the lowest-frequency comb tooth.* ❷ *Optical lock of one of the optical comb teeth ν_n to an external optical reference frequency ν_{cw}.* ❸ *Pinning the comb spectrum at both ends (f_{ceo} and ν_n) dramatically stabilizes the line spacing (f_{rep}) of all of the comb teeth. The frequency line spacing will have a frequency stability (δf_{rep}) that is n-times better than the frequency stability of the external optical reference frequency ($\delta\nu_{cw}$), with n being on the order of 10^5 - 10^6.*

Such an optical lock operates by continuously measuring ν_n against the optical reference frequency ν_{cw} (via a beat signal f_{beat}), detecting any drift, and applying a feedback loop to keep the comb tooth precisely aligned. As a result, the frequency stability of the external optical reference frequency can be entirely transferred to the comb tooth.
The core principle of optical frequency division is that pinning the comb spectrum at both ends (i.e. at f_{ceo} and ν_n) dramatically stabilizes the line spacing (f_{rep}) of all of the comb teeth (Fig. 2 / ❸). Intuitively, this happens because fluctuations are divided over the entire frequency span between the two pinning points.
Switching to the time domain (Fig. 3), the periodic pulse train generated by the laser consequently undergoes a dramatic reduction in timing jitter (Fig. 3 / ❹). When such a pulse train impinges on a suitable photoreceiver (Fig. 3 / ❺), it generates an RF signal at the repetition rate frequency f_{rep} with ultralow phase noise (Fig. 3 / ❻).

It takes only a little mathematics to convey the power of optical frequency division. Considering the beat signal

$$f_{beat} = \nu_{cw} - \nu_n$$

between the optical reference frequency (ν_{cw}) and the optical frequency of the n-th comb line (ν_n), and inserting for ν_n from the comb equation gives the relation

$$f_{beat} = \nu_{cw} - (f_{ceo} + n\, f_{rep})$$

If the locking is assumed to be “perfect”, fluctuations in f_{beat} will vanish

$$\delta f_{beat} = 0$$

which translates into

$$\delta\nu_{cw} - \delta f_{ceo} - n\, \delta f_{rep} = 0$$

Rewriting the above equation for fluctuations of the repetition rate gives

$$\delta f_{rep} = (\delta\nu_{cw} - \delta f_{ceo}) / n$$

Since in practice, δf_{ceo} can be brought down to zero, the above equation simplifies to

$$\delta f_{rep} = \delta\nu_{cw} / n$$

i.e. the fluctuations the optical reference frequency $\delta\nu_{cw}$ are divided down by the mode number n. In other words, the frequency line spacing (respectively the repetition rate f_{rep}) will have a frequency stability that is n-times better than the frequency stability of the external optical reference frequency ν_{cw} - with n being on the order of 10^5 - 10^6 (Fig. 4).

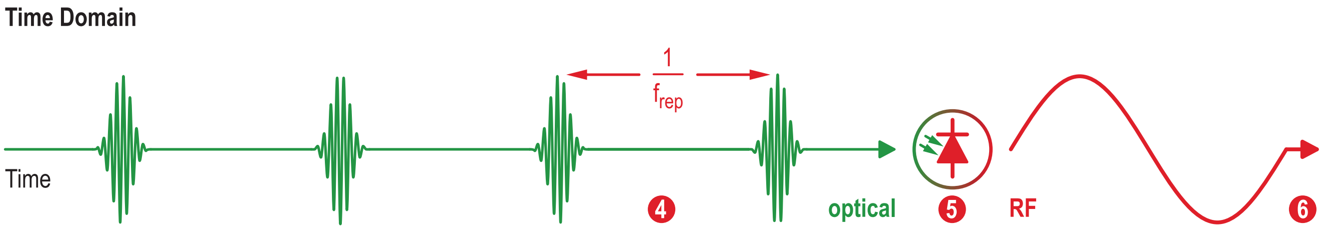

Figure 3. *Time domain perspective of optical frequency division.* ❹ *A periodic pulse train that has undergone a dramatic reduction in timing jitter.* ❺ *The pulse train impinges on a suitable photoreceiver.* ❻ *An ultralow phase noise RF signal at the repetition rate frequency f_{rep} is generated.*

ULTRASTABLE MICROWAVE SYSTEMS

In summary, ultrastable microwave systems lock the electromagnetic field of an optical reference to an optical frequency comb, allowing the comb to divide it down to an ultrapure RF signal, which is then extracted using suitable opto-electronics. Accordingly, such systems comprise three key sub-units: (1) an ultrastable optical reference, acting as a flywheel, (2) an optical frequency comb, functioning as a reduction gear, and (3) an RF extraction unit, tailored to the desired RF output frequency. Each of these components involves intricate details that are, in themselves, a refined art of engineering.

Menlo Systems' ultrastable microwave systems are the result of years of dedicated research, development, and integration design. In 2016, we set a world record for the lowest phase noise on an X-Band microwave signal[1] - a record that still stands today. In 2019, we prototyped the very first fully-integrated, transportable system[2].

Today, we are delivering this exceptional performance through fully-integrated solutions that bring together the entire breadth of our expertise:

- **Unrivaled in performance.**
  Delivering the lowest phase noise on the market through optical frequency division technology - as the industry's only validated commercial supplier to date.

- **Endorsed by experts.**
  Performance consistently trusted by national metrology institutes, radar system scientists, and leading electronic test equipment manufacturers alike.

- **Versatile by design.**
  Application-tailored frequency stability solutions, form factors, and input/output configurations to cover use case specific RF, microwave, and optical frequencies.

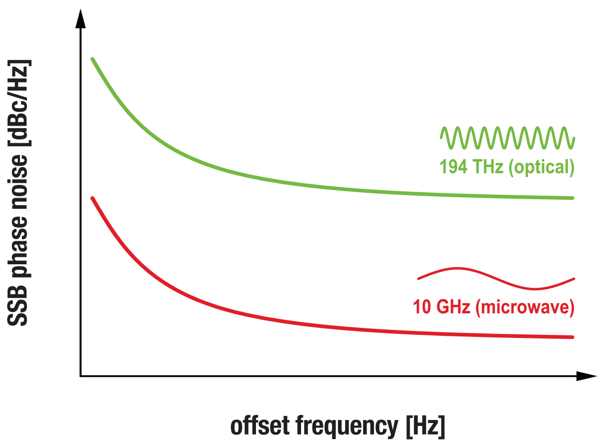

Figure 4. *Phase noise reduction in optical frequency division. Assuming a common optical frequency reference at 194 THz, the potential phase noise reduction factor for a 10 GHz microwave carrier amounts to -86 dB.*

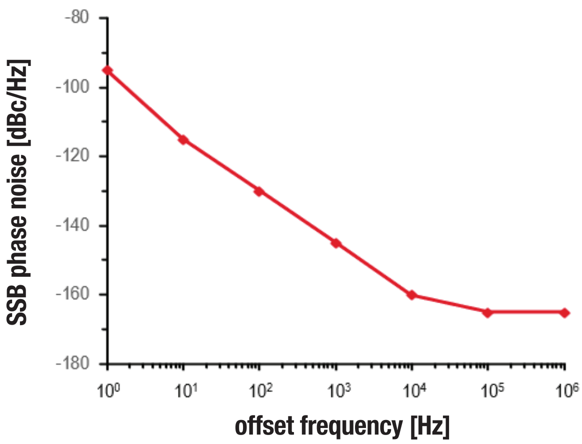

Figure 5. *Example of real-world phase noise performance of an ultrastable microwave system (UMS-Compact) for a 10 GHz microwave carrier.*

[1] Photonic microwave signals with zeptosecond-level absolute timing noise, X. Xie et al., Nature Photonics (2016), 11, 44–47
[2] Compact and ultrastable photonic microwave oscillator, M. Giunta et al., Optics Letters (2020), 45, 1140

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