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Frequency modulated combs using semiconductor lasers

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Most comb research is focused on the generation of pulses. However, frequency combs can also exhibit a very different behavior that is characterized by a continuous output intensity – the frequency modulated (FM) comb regime. Here, we present our theory including to describe the involved physical mechanisms and explain which conditions need to be fulfilled to generate self-starting FM combs in semiconductor lasers [1]. We show that in fast gain media, such as quantum cascade lasers (QCLs), our theoretical model can be reduced to a single master equation:

$$\begin{aligned}\left(\frac{n}{c}\partial_t \pm \partial_z\right)E_\pm = \frac{g(P)}{2}\left[E_\pm - T_2\partial_t E_\pm + T_2^2\partial_t^2 E_\pm\right] - \frac{g(P)T_g}{2T_1 P_{\mathrm{sat}}}\Big[|E_\mp|^2 E_\pm - (T_2+T_{\mathrm{g}})|E_\mp|^2\partial_t E_\pm \\ -(T_2+T_{\mathrm{g}})E_\pm E_\mp \partial_t E_\mp^* - T_2 E_\pm E_\mp^* \partial_t E_\mp\Big] + i\frac{k''}{2}\partial_t^2 E_\pm + i\beta\left(|E_+|^2 + |E_-|^2\right)E_\pm - \frac{\alpha_w}{2}E_\pm.\end{aligned} \tag{1}$$

Different to the Haus equation [2], this equation includes spatial hole burning and further phase sensitive terms, which appear to be crucial to describe the physics of FM combs. It can be shown mathematically that neglecting these terms is tantamount to neglecting the phase dynamics of the gain medium and thus the appearance of the FM comb.

Using our new insights we will discuss experimental observations of FM combs in QCLs [3, 4], as well as lasers with slower dynamics, such as interband cascade [5], quantum well and quantum dot laser [6]. As a main characterization technique, we use the linear RF phase measurement technique shifted wave interference Fourier transform spectroscopy (SWIFTS). A detailed comparison between SWIFTS and the intensity autocorrelation for the pulse shape characterization will be presented. A more intuitive picture of the synchronization states in frequency combs is provided by the analogy to coupled clocks, which reveals a illustrative understanding of how these lasers can be tuned into either the pulsed (AM) or the FM comb regime [6]. Using this knowledge we finally demonstrate the first AM mode-locked mid-infrared QCL at 8 µm operating at room-temperature with transformation limited pulses as short as 6.5 µs.

References

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