Phase-locked white-light continuum pulses: towards a universal optical frequency comb synthesizer

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Recent experiments [1, 2] have shown that trains of ultrashort laser pulses are a powerful tool to measure optical frequencies with very high precision. The comb of frequencies (spaced by the known pulse repetition rate) which constitutes the spectrum of a mode-locked laser can be used as a ruler to measure frequency differences up to tens of THz with an accuracy of a few parts in 10^{17}. The largest measurable frequency gap is determined by the bandwidth of the laser radiation and, for transform-limited pulses, the shorter the pulse, the larger is the frequency interval available. A mode-locked laser with a pulse duration of about 75 fs was used in Ref.[1] to measure a frequency gap of about 18 THz and determine the absolute optical frequency of the Cesium D_1 line at 895 nm to parts in 10^{10}, while a comb broadened to more than 50 THz by self-phase-modulation (SPM) in a nonlinear optical fiber has been used in a recent absolute frequency measurement of the hydrogen 1S-2S interval [2]. In order to bridge even larger frequency gaps and eventually build a universal optical frequency-meter across the whole visible and extending in the near UV and IR parts of the spectrum, even broader combs are needed.

One way to achieve such an extreme spectral broadening is through the process of white-light continuum generation, obtained by focusing intense laser pulses into most transparent materials. Being the result of a very complex interplay between competing linear and nonlinear processes (dominated by the SPM of the pulse due to an intensity dependent refractive index of the medium), the exact characteristics of the output continuum appear strongly dependent on the exact initial conditions of the interaction and hardly predictable. In particular, one is led to expect that the white-light pulses produced by phase-locked pump pulses have lost any precise phase relationship in the generation process. Considering that the phase coherence among successive pulses in the train is an essential ingredient for the generation of a broadband frequency comb, such white-light pulses may appear inadequate for this purpose.

We have tested the phase coherence of pairs of supercontinuum pulses by performing an experiment related to Young's double slit experience: here two white-light pulses are generated independently at different positions in a transparent medium by two phase-locked laser pulses (see inset of Fig.1). Our results are rather intriguing: when the two pump pulses are adjusted for equal intensity and zero relative delay, the two white-light continua that they generate independently show surprisingly clear and stable interference fringes, indicating that we are dealing with highly phase-correlated secondary sources.

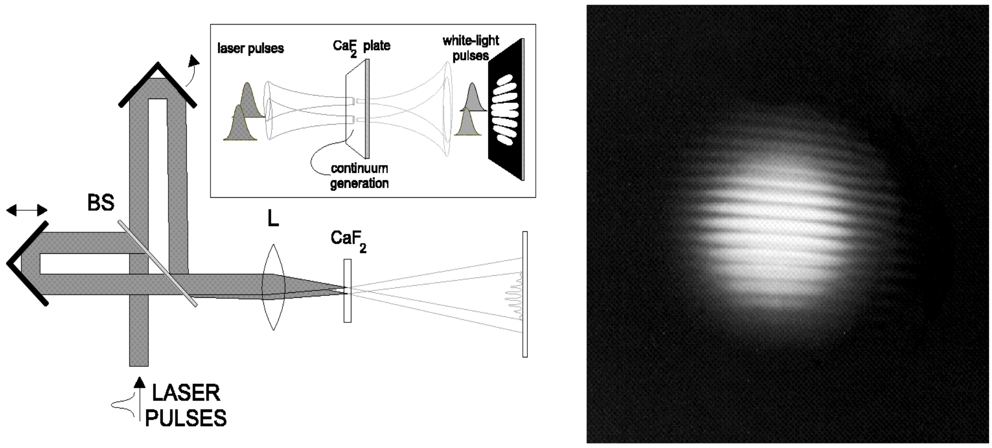

Figure 1: Experimental setup and observed white-light interference fringes.

We want to emphasize that there is a substantial difference between this and a simple Young's or Michelson's type experiment: while in these cases two spatial portions of the same beam, or two time-delayed replicas of the same pulse are recombined to give interference, in our experiment the interference fringes appear because of the spatio-temporal superposition of two white-light pulses that are generated in an independent way in two separate positions of the medium and that, for the reasons discussed above, might be expected to be highly uncorrelated.

For a frequency comb measurement, the separation among the modes in the comb should be of the order of hundreds of MHz so that a simple wavemeter is sufficient to unambiguously count the integer number of spanned modes by an accurate preliminary determination of the unknown frequency gap. Though it was not possible so far to generate a white-light continuum with the low peak intensities available to unamplified mode-locked systems (with the required high repetition rates), recent reports [3, 4] have demonstrated that *photonic crystal fibers* allow the generation of a supercontinuum directly from the output of a mode-locked femtosecond laser with pulse energies of a few nJ or below. The experiments reported here suggest that supercontinuum generation in such fibers might be the key to the realization of a working prototype of a universal frequency synthesizer.

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