Wideband Nonlinear Optics

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http://www.lsr.ph.ic.ac.uk/ http://www.kinsler.org/physics/ Talk; Abstract;

ECLEO 2003, Munich: postdeadline talk.
Original Title: *“Near-degenerate few-cycle optical pulses”*

Motivation

⧫ Few cycle pulses are being made in the laboratory...
  – *"Five-optical-cycle pulse generation..."* Beddard et.al. (2000).

★ Why not a FDTD solution of Maxwell's equations?
  – Pulse envelope approaches are faster and more intuitive...
  – hence our GFEA (Kinsler & New (2003))
  – cf the SVEA and SEWA (Brabec & Kraus (1997)).

▶ We need a *wideband non-linear optics (WNLO)*
  → even without near-degeneracy (hence the change of title).

▶ *Two and a half step program* to WNLO
  – few-cycle propagation (GFEA)
  – off-resonant polarization terms
  – (spectral management)

Summary

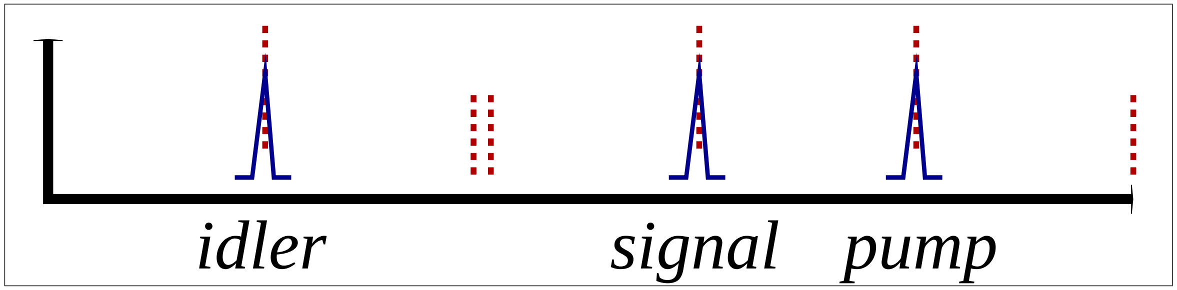
Narrowband NLO → Wideband NLO → Overlap → Solitons → OPO:few-cycle → OPO:polarization → OPO: spectra → Conclusions

Narrowband Non-linear Optics

■ The total field is split up into components according to the type of process under investigation: e.g. in an OPO, with a $\chi^{(2)}$ interaction, we split the field up into a pump, signal, and idler (carriers $\omega_p, \omega_s, \omega_i$; & $E = E_p + E_s + E_i$).

■ The spectra of the components are narrow, and don't overlap. They vary slowly w.r.t. their carrier ω_α, so we can propagate them using the SVEA.

■ The total polarisation $\chi^{(2)} \left(E_p + E_s + E_i\right)^2$ gives us many nonlinear terms, but we only need to keep those exactly on resonant with our chosen frequencies. E.g. in an OPO with a *near-IR* idler, only the $\omega_p - \omega_s$, $\omega_p - \omega_i$, and $\omega_s + \omega_i$ terms are needed.



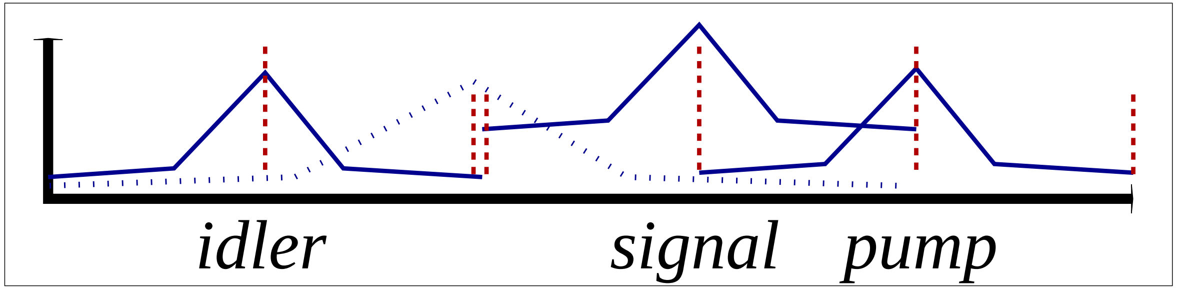
► We ignore the frequency doubled idler ($2\omega_i$); also $\omega_s - \omega_i$, $\omega_p + \omega_i$, ...

Wideband Non-linear Optics

■ The total field is split up into components according to the type of process under investigation: e.g. in an OPO, with a $\chi^{(2)}$ interaction, we split the field up into a pump, signal, and idler (carriers $\omega_p, \omega_s, \omega_i$; & $E = E_p + E_s + E_i$).

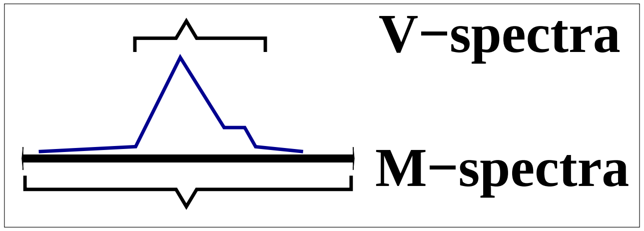
■ A wideband spectra can mean rapid variation of the pulse w.r.t. its carrier oscillations. This breaks the slowly-varying envelope approximations. *We therefore need to use a few-cycle theory such as the GFEA.*

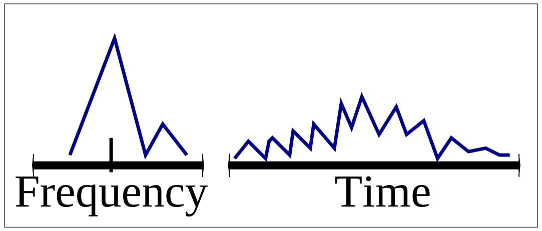
■ The general form of the polarisation $\chi^{(2)}\left(E_p + E_s + E_i\right)^2$ gives us many nonlinear terms: we need to keep those which are on resonant with our chosen frequencies, *and those which appear in range of the field spectra.* E.g. in an OPO, extra terms like the $2\omega_i$ or $\omega_s - \omega_i$, or $\omega_p + \omega_i$.



Spectral Overlap & Management

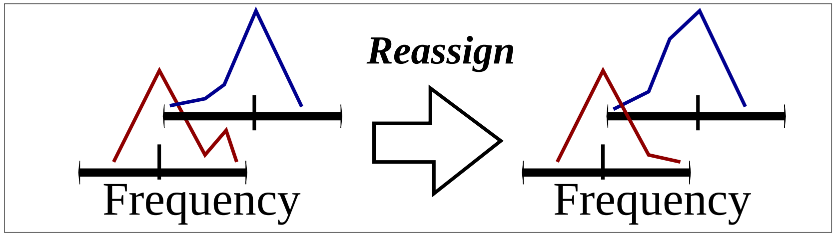
■ A numerical simulation fixes a spectral width for each field being modelled (“M-spectra”)... but it is usually only the spectral values stored within them (“V-spectra”) that concern us.





■ A detuned spectral peak can disrupt time domain smoothness! ⇑

■ If the M-spectra overlap, we could re-assign spectral components by building a total spectra. We might then redivide it according to the nearest carrier frequencies, ⇓, aiming to smooth the pulse envelopes.



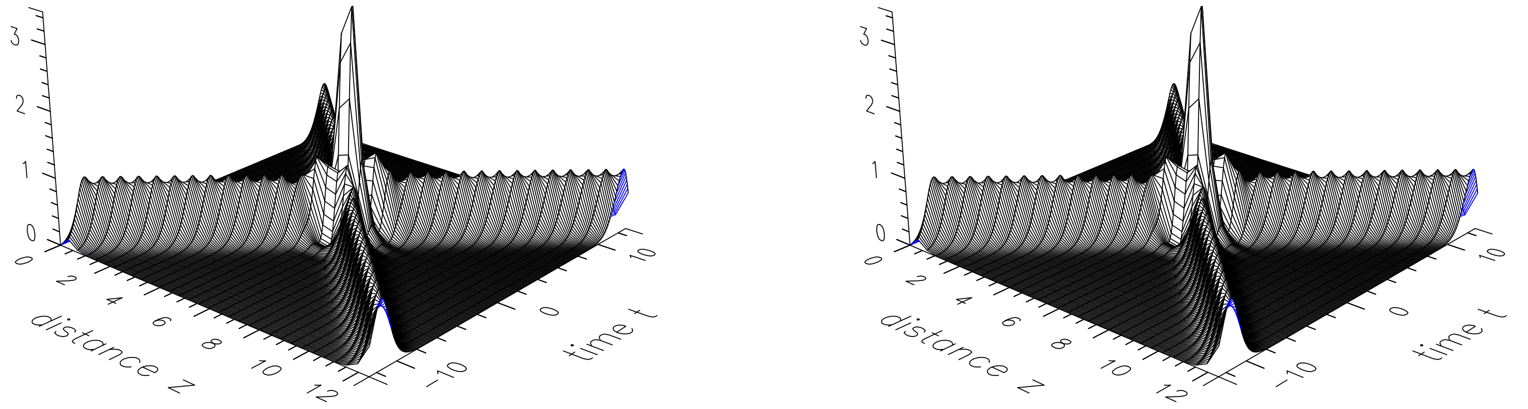
NLS Solitons

■ NLS solitons propagate and collide without changing, detuned solitons change speed – all according to:

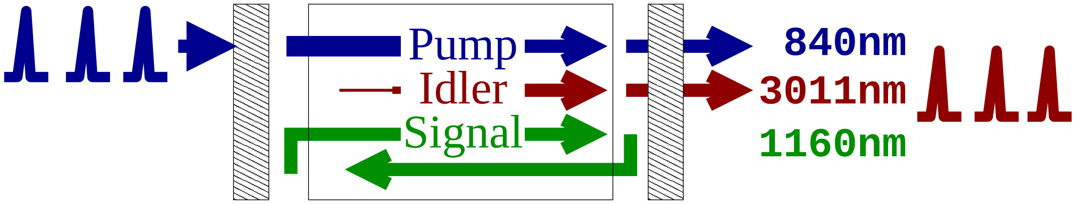
$$\partial_\xi A(\xi,\tau) = \imath\beta_1\partial_\tau A(\xi,\tau) - \frac{\beta_2}{2}\partial_\tau^2 A(\xi,\tau) + \frac{2\imath\pi}{n_0^2} A(\xi,\tau)^* A(\xi,\tau)^2, \qquad (1)$$

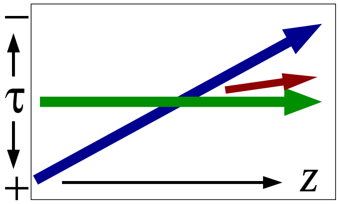
■ We launch a pair of near-degenerate (oppositely detuned) solitons, with the faster one overtaking the slower: simulate with (LHS) one envelope, or (RHS) as two envelopes by including "off-resonant" polarization terms:

$$\chi^{(3)}\left(E_1+E_2\right)^3 = \chi^{(3)}\left(A_1+A_1^*+A_2+A_2^*\right)^3 \Rightarrow A_1^*A_1^2 + A_1^*A_1A_2 + A_2^*A_2A_1 + A_2^*A_2^2. \qquad (2)$$

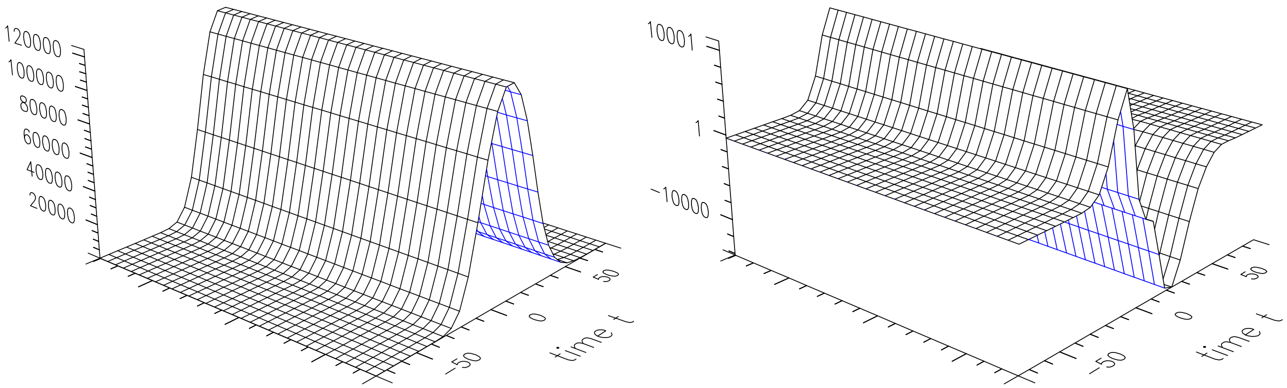


OPO: Few-cycle effects





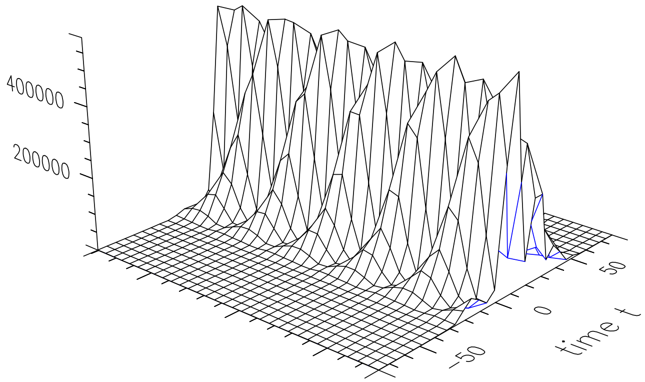
► Wide bandwidth pulses go together with few-cycle pulses. The addition of FC effects on OPO predictions varies: although the output pulse lengths are similar, pulse shape and the phase properties of the pulse can vary greatly (see Kinsler & New (2003)). *With added FC effects:*

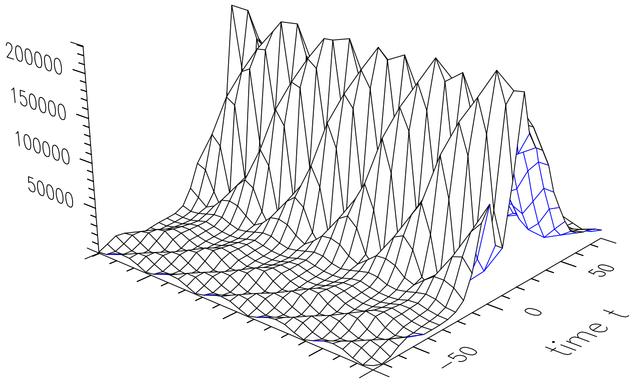


12fs Pump Pulse: ⇑ GFEA Idler and ⇑ difference from SVEA

OPO: Off Resonant Polarization

► Wide bandwidth pulses also mean that off-resonant polarization (ORP) terms need to be included. These have a significant effect on the OPO output – pulse profiles are unstable, pulse lengths change. *Adding ORP effects:*





12fs Pump Pulse: ⇑ Idler ⇑ Signal

OPO: Spectral Management

► Wide bandwidth pulses mean that our field component envelopes can overlap in frequency space – we need to treat this carefully to avoid introducing (model) implimentation dependent effects.

Conclusions

▶ **Theory & Implementation:** Wideband Nonlinear Optics

★ **NLS Solitons:** colliding, near-degenerate solitons conveniently demonstrate spectral overlap and the need for off resonant polarization terms.

▶ **Wideband NLO: short pulses –** the GFEA gives few-cycle pulses a "phase-twist" during propagation.

▶ **Wideband NLO: polarization –** It is vital to include all relevant polarization terms.

▶ **Wideband NLO: spectral management** ...

Links

- ▶ **Kinsler & New:** Phys. Rev. A**67**, 023813, (2003)
  Preprint: http://arXiv.org/physics/0212016
  Detailed Calculation: http://arXiv.org/physics/0212014
  Web: http://www.qols.ph.ic.ac.uk/~kinsle/
  Web: http://www.kinsler.org/physics/
- ▶ **Brabec & Krausz:** Phys. Rev. Lett. **78**, 3282 (1997)
  http://link.aps.org/abstract/PRL/v78/p3282
- ▶ **Beddard,** Ebrahimzadeh, Reid, Sibbett: Opt. Lett. **25**, 1052 (2000)
  http://ol.osa.org/abstract.cfm?id=62075
- ▶ **Biswas & Aceves:** J. Mod. Opt. **48**, 1135 (2001)
- ▶ **Wabnitz, Kodama & Aceves:** Opt. Fiber. Technol.**1**, 187 (1995)

Few-Cycle Theory

■ **An exact propagation equation for** $A(\xi,\tau)$ with $B(\xi,\tau;A)$ ...

$$\partial_\xi A = \left(-\frac{\alpha_0}{\beta_0} + \imath \hat{D}'\right) A + \frac{\imath/\left(2\beta_0^2\right)}{\left(1+\imath\sigma\partial_\tau\right)} \nabla_\perp^2 A + \frac{2\imath\pi}{n_0^2} \frac{\left(1+\imath\partial_\tau\right)^2}{\left(1+\imath\sigma\partial_\tau\right)} B + \frac{T_{RHS}}{1+\imath\sigma\partial_\tau}.$$

☐ **GFEA:** *Generalised Few-cycle Envelope Approx.* (Kinsler & New (2003)) using $T_{RHS} = 0$. Our new approximation that includes all time-dependent corrections to the nonlinear polarization. Aka “Generalised Finite Envelope Approx”.

► **Approximations used are** (1) Slow Evolution, (2) Weak Dispersion, (3) Weak Diffraction, (4) Weak Nonlinearity

☐ **SVEA:** *Slowly-Varying Env. Approx.* $\partial_\xi A_{NL} = BA.$

☐ **SEWA:** *Slowly-Evolving Wave Approx.*, Brabec & Krausz. $\partial_\xi A_{NL} = \left(1+\imath\partial_\tau\right) B.$

► Expansion of few-cycle polarization terms:

$$1 + \imath\left(2-\sigma\right)\partial_\tau - \left(1-\sigma\right)^2 \partial_\tau^2 + \imath\sigma\left(1-\sigma\right)^2 \partial_\tau^3 + \mathcal{O}(\partial_\tau^4).$$

Notes

► Motivation: Talk renamed from “Near-degenerate few-cycle optical pulses” because I can see wideband effects without even looking at near-degenerate systems.

★ Narrowband NLO: Of course which polarization terms we need depends on our choice of carrier frequencies and other model-based considerations.

★ Wideband NLO (ORP): Note the width of the (dotted line) frequency doubled idler – even if you want to believe the off-resonant polarization terms are centered far from the field carriers, the spectral width of those terms guarantees problems.

★ Wideband NLO (SM): with wideband spectra, spectral sidebands can be far from the center (carrier) frequency, leading to fast (non-slow) time variations. *This is important* because such variations break our pulse propagation.

★ Wideband NLO (SM): Of course we will not want to do a customised management at every step, we just want some suitably smooth “interpolation” scheme.

► NLS Soliton: The one-envelope simulation has a double peak initial condition corresponding to double sideband-solitons. The two-envelope simulation has two separate individually described peaks.

► NLS Soliton: The two-envelope results have the individual envelopes combined into one piece.

► NLS Soliton: dispersion is table of single quadratic about center frequency.

★ OPO sims: based on a 11nJ 24fs pump pulse reference, crystal length 512μm, with other system parameters scaled so as to make the output scale invariant in the narrowband SVEA case; assumes an ideal periodic poling period which perfectly phase matches components at the carrier frequencies. NB: (0.75^2) lower than 20nJ in Kinsler & New (2003) (hence simple idler profile).

★ OPO sims: Perfectly phase matched at carrier frequencies by periodic poling; dispersion table from quadratic expansion about carriers; synchronisation set to 0fs; ±190fs time windowing before input mirror (t^8 super-gaussian).

★ OPO sims: dispersion table from quadratic expansion about carriers, reference $LiNO_3$ at 24fs.

★ OPO sims: Mirrors: asymmetric top-hat band pass
mirror spectrum: $\omega \in [0.00, 1.11) \rightarrow 0.0100$
mirror spectrum: $\omega \in [1.11, 1.92) \rightarrow 0.8400$
mirror spectrum: $\omega \in [1.92, \infty) \rightarrow 0.0001$

★ OPO sims: sequence: output; $\chi = 0$ crystal; synchronisation; time window; input mirror; crystal; *then repeat*.

★ OPO sims: GFEA and SVEA *intensity* profiles similar, but note timing shift from RHS difference graph.

★ OPO sims ORP: despite the ORP contributions not being phase matched, they drive the pulses strongly enough to make their transit-to-transit profiles wobble – this is stronger for higher powers and shorter pump pulses.