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First … student competition

- Write a 500-1000 word popular article about your research, due: 14 July
- 1st prize $1000, 2nd prize $250, certificates + COSMOS magazine paraphernalia
- Winners announced at Hervey Bay workshop
- Good entries considered for web posting, publication
- Exposed to professional science communicators
  - David Ellyard–National Council of Australian Science Communicators
  - Sara Phillips–editor, COSMOS magazine
  - Ross McPhedran–CUDOS.

Applications of slow light - optical buffers

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Centre for Ultrahigh bandwidth Devices for Optical Systems

An Australian Research Council Centre of Excellence

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Relevant papers

- JB Khurgin, “Optical buffers based on slow light in …,” JOSA B **22**, 1062 (2005).
- RW Boyd, DJ Gauthier, AL Gaeta, and AE Willner, “Maximum time delay achievable on propagation through a slow-light medium,” PRA **71**, 23801 (2005).
- G Lenz, BJ Eggleton, CK Madsen, and RE Slusher, “Optical delay lines based on optical filters,” JQE **37**, 525 (2001).
- RS Tucker, P-C Ku, CJ Chang-Hasnain, “Slow-light optical buffers: capabilities and fundamental limitations,” JLT **23**, 4046 (2005).

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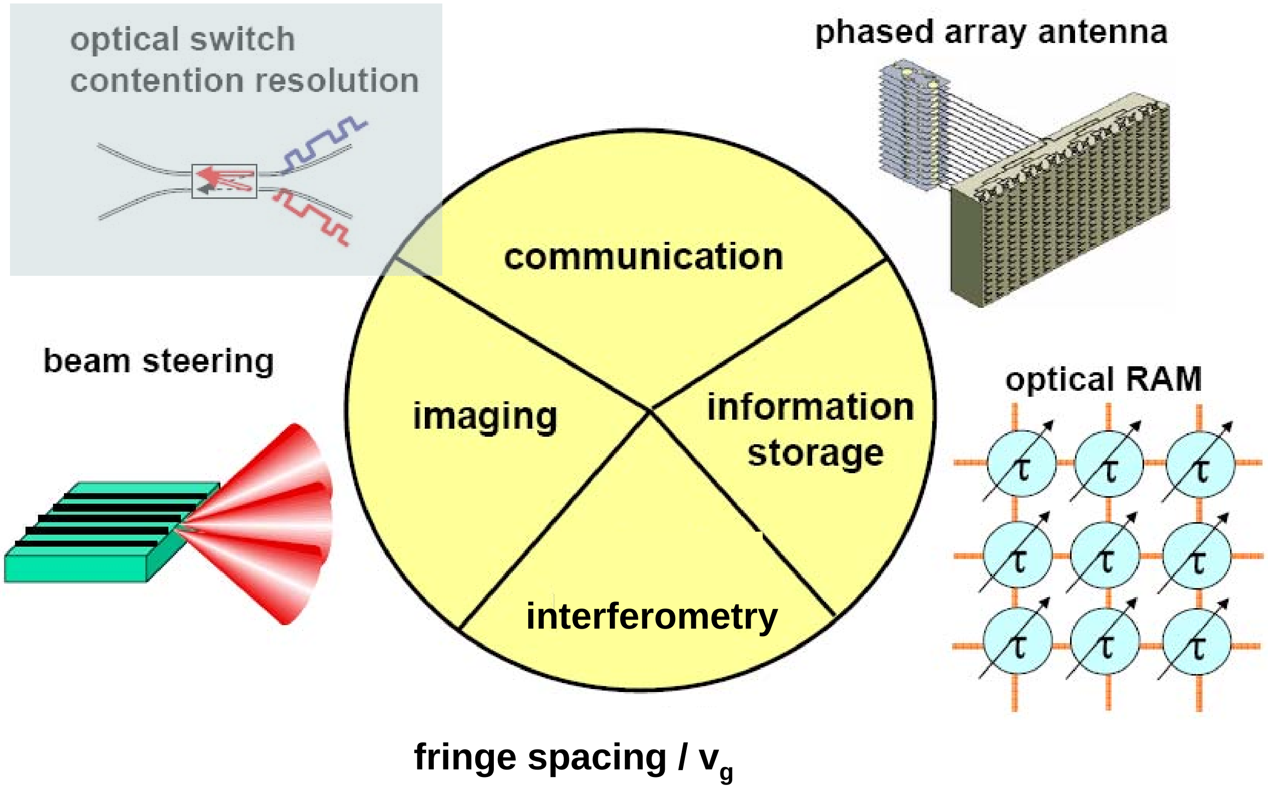
Outline

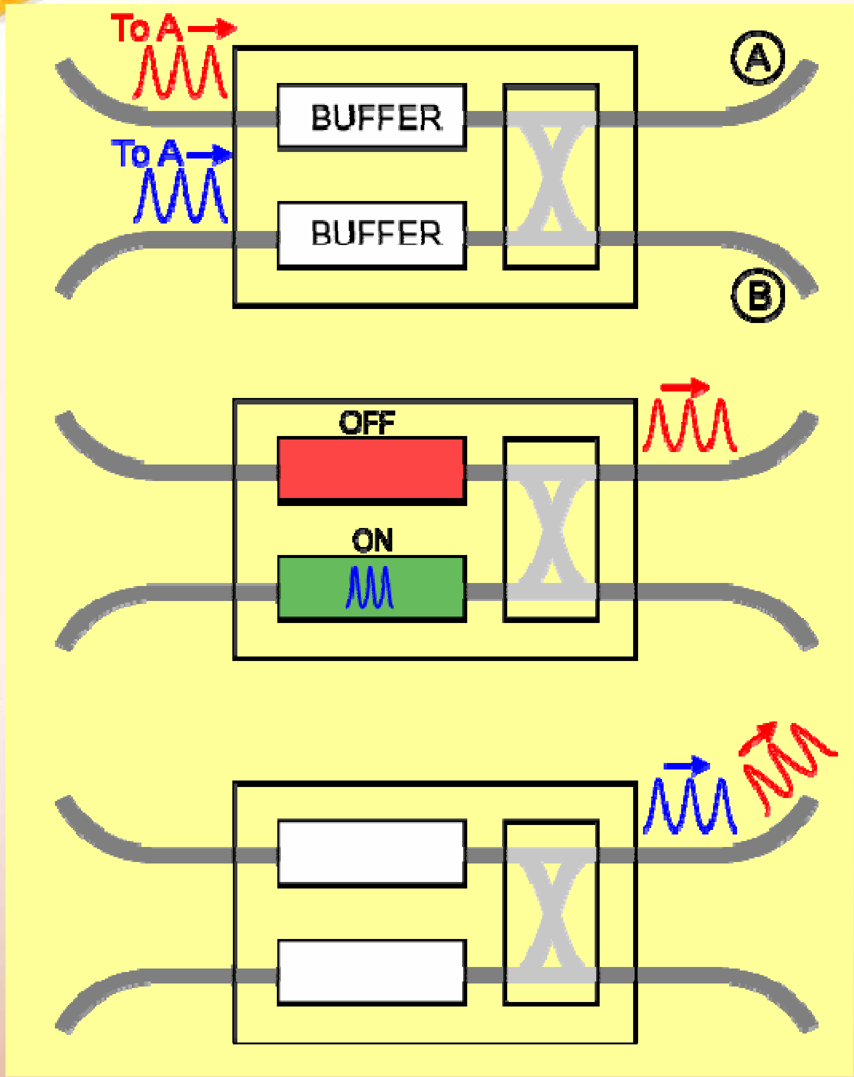
- Intro: why slow light—buffers
- What are the issues to consider?
  - Losses
  - Dispersion
- Outro—what have we learned?

Why slow light?

Scope of applications



Contention resolution–buffer



Currently done using electronics, but will run out of steam with increasing bit rates

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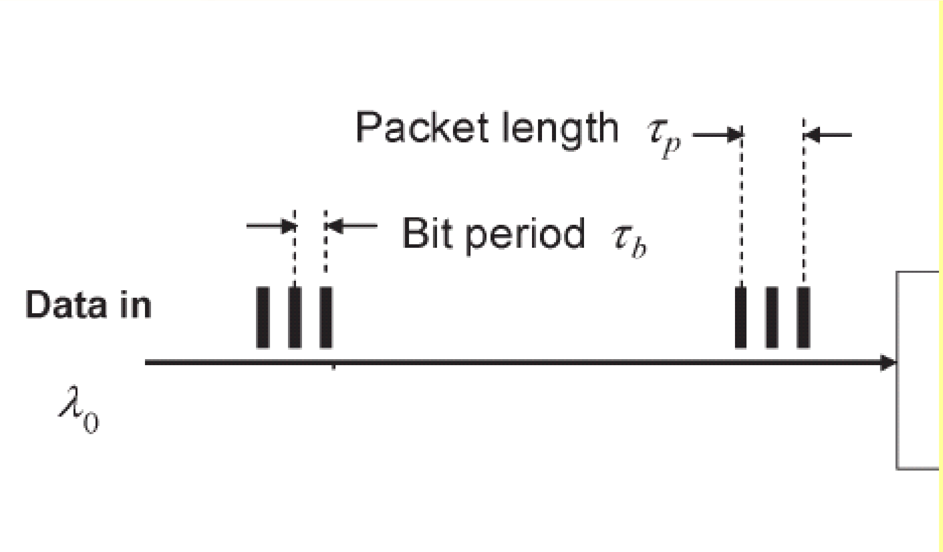
An engineer's view



In fact the issue of # bits per packet τ_p/τ_b is one of the great unknowns in this story. It is important as it tells you the required buffer Capacity C.

Tucker *et al* make no statement (picture shows τ_p/τ_b=3). Boyd *et al* work with τ_p/τ_b=1000, while Khurgin hedges his bets taking τ_p/τ_b=20,50,100. I'd suspect that the final number will depend on what can be achieved with slow light devices.

- Note:
  - # bits per packet: τ_p/τ_b
  - Bandwidth B¼1/τ_b
  - Capacity of buffer $C=T_s/\tau_b=$
- Key element: variable delay— tunable slow light

A physicist's view

- Recall:

$$\frac{1}{v_g} = \frac{dk}{d\omega} = \frac{d}{d\omega}\frac{\omega n}{c} = \frac{1}{c}\underbrace{\left(n + \omega\frac{dn}{d\omega}\right)}_{n_g}$$

- Thus, need a feature in dispersion relation where refractive index varies rapidly with frequency
- Two issues come up:
  - Rapid variation cannot go on indefinitely—must have dispersion
  - By Kramers-Kronig, such a feature associated with loss
- Both limit the capacity of the delay line

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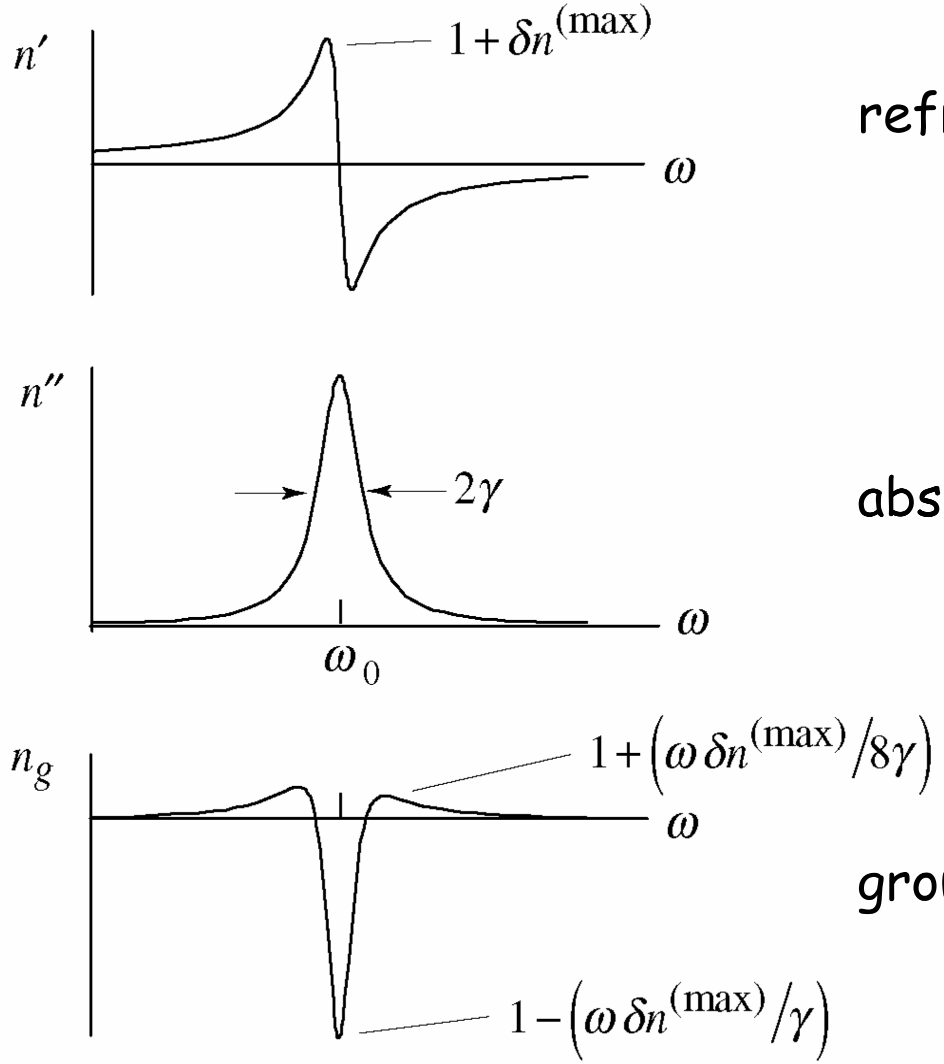
Illustration: generic resonance



refractive index

absorption

group index $\left(n_g = n + \omega\frac{dn}{d\omega}\right)$

Effect of losses

- Losses clearly limit buffer ler
achievable delay. Tucker *et a*
and show that for ideal slow-l

$$C^{\text{ideal}} \equiv BT_S = \frac{T_S}{\tau_b}$$

- where $L^{\text{ideal}}_{\text{bit}}$ is the length per
- Can show that in general (not in paper):

$$\alpha < \frac{B\,\Delta n_g}{bc} \approx 11\ \text{dB/m}$$

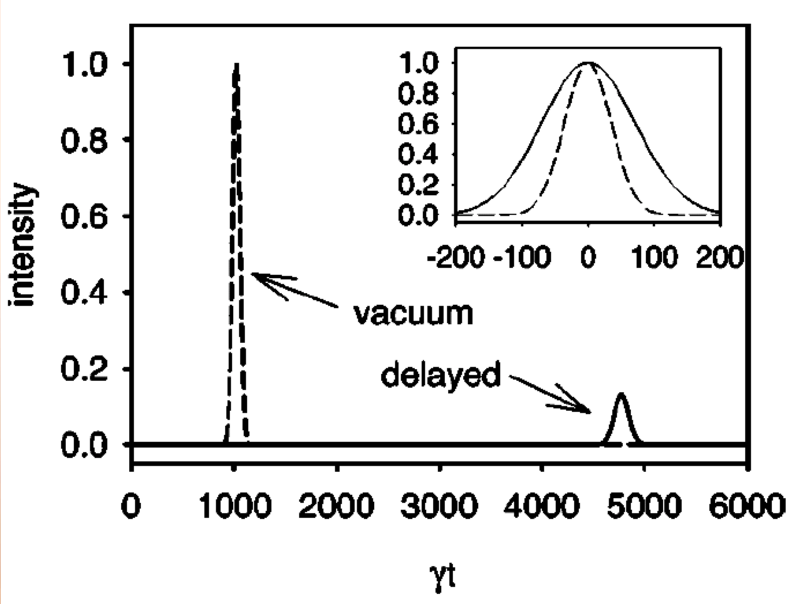
Bandwidth B=40 Gb/s
Δn_g=1
b=τ_p/τ_b=50

Their detailed argument relies on the requirement that the entire packet fit inside the buffer. I do not know if this is truly always needed or if it is a feature of their embodiment.

Nonetheless, it is clear that losses limit the performance of a buffer.

Effect of losses

- Boyd *et al* very worried by "residual" losses and think it is the limiting factor (use population oscillations—Andrey's talk). Relies on nonlinear loss reduction from αLÀ1 to α¼0—very delicate.
- Numerical ex: αL=7500 (T<-65 [...]



It is certainly easy to poke fun at this latter assumption. However, I truly do not know how realistic it is. Certainly at Photonics West earlier this year Boyd used the word "heroic" in this context!

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Effect of dispersion

The literature is confusing on this point:

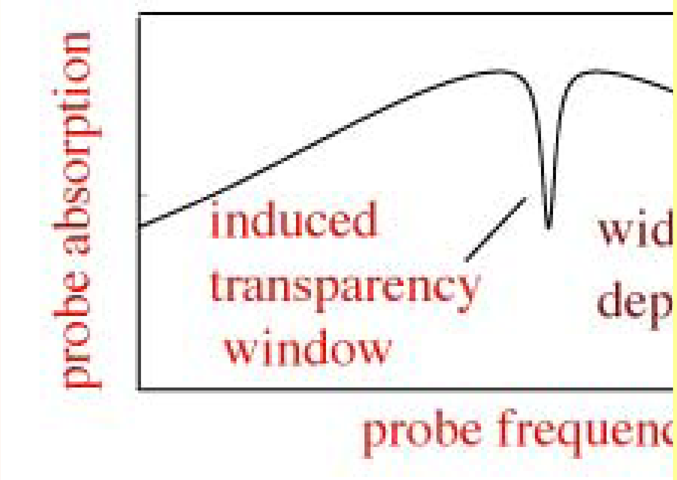
- Lenz *et al*: "This can be summarized by the … relation:

  $$\tau_{\max}\Delta\omega \cong \text{constant}$$

  where τ_{max} is the maximum delay of the device and $\Delta\omega$ is the bandwidth over which this delay is achieved."
- Boyd *et al*: "If one can eliminate residual absorption, the maximum relative time delay … has no upper bound."
- Khurgin (see Mike's talk) answers a different question: "Thus based on dispersion limitations, the Coupled Resonator Structures buffer is expected to outperform greatly the Electromagnetically Induced Transparency buffer at large bit rates and storage capacities."

Boyd's argument–preliminaries

- Absorption of weak probe (pul



- "We emphasize that there is r … γT_0 can become. Indeed, one the pulse duration T_0 to be lor so that the … spectrum of the e transparency window."

The point down the bottom is interesting: many others try to "milk" the available bandwidth completely. Boyd *et al* purposely do not do this—they choose to use only a small fraction. Thus, in some sense, they waste the available bandwidth. This is the key to the results on the next slide.

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Boyd's argument, then

- Associated dispersion (by K
  cubic in the centre

- Demand that pulse's dispers
  than its width. Then find fo

$$\left(\frac{T_{\rm del}}{T_0}\right)_{\rm max} =$$

since γT_0 can be arbitrarily
upper limit.

The argument is interesting: even though the ratio T_{del}/T_0 gets smaller when T_0 goes up, you get recompensed elsewhere:

•Since T_0 larger, can tolerate more dispersion;

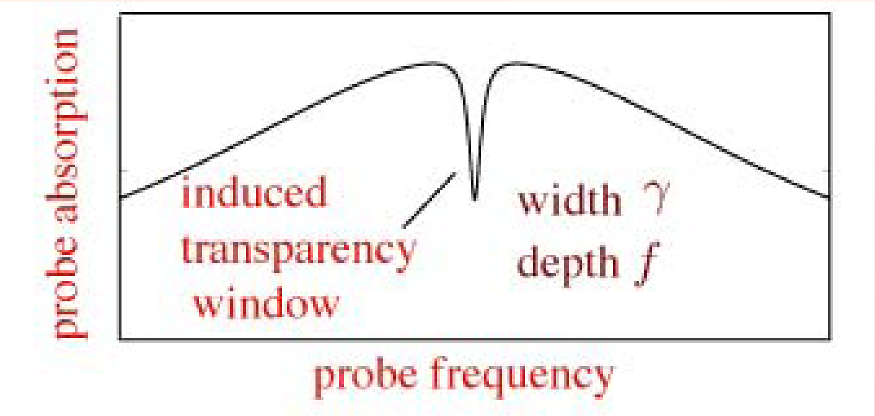
•Since bandwidth down, dispersive effect down too. Since limited by *cubic* dispersion this is particularly important.

However, the more you use this ploy, the more bandwidth you waste!

Boyd's argument, continued

- In fact, effect of differenti
restrictive criterion: pulse sp
pulse width increases; leads t

$$\left(\frac{T_{\mathrm{del}}}{T_0}\right)_{\max} =$$



It is rather ironic that worries about the effect of dispersion do not even rank in the top two! Of course this is partly so because the quadratic dispersion at the absorption feature's centre disappears, so that narrowing the bandwidth pays off handsomely. However, even if the quadratic dispersion did vanish then T_{del}/T_0 would scale linearly with γT

Lenz's argument

- Considers somewhat more abstract general all-pass linear filter as archetypal system—constant amplitude response, but phase response is not.
- Response is periodic in fre
- Spectral Range")
- Introduce parameter Δ, th
  - Maximum delay: 2/(Δ ω_{FSR})
  - Bandwidth, as defined by th
- So product of delay and bo

Notice the key difference with Boyd's approach:

•Boyd defines the bandwidth as the inverse of the pulse length, and thus derives it from the signal.

•Lenz defines the bandwidth as the width of the dispersion feature of the device, without direct reference to the signal.

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What does this mean?

- So Boyd *et al* and Lenz *et al* use different definitions of the bandwidth.
  - Boyd defines in terms of what is needed (by the signal)
  - Lenz by what is available (by the device).
- This difference in definitions leads directly to the different conclusions. Since

  if I use Boyd's definition of bandwidth and apply it to Lenz's system, then I draw Boyd's conclusion.
- So, again, definition drives the conclusion

Outlook

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- Is there a "canonical" definition of bandwidth for this type of instance?
- I probably prefer Lenz' definition since Boyd's is spectrally wasteful.
- Note that other papers, not discussed here, define bandwidth in a way similar to Lenz, ie, via the width of a spectral feature of the device.
- There are more criteria than dispersion by which to judge a slow light device
  - Absorption losses
  - Physical size of a bit (Tucker *et al*).

Intuition behind Lenz' finding

- Recall that $n_g = n + \omega(dn/d\omega)$
- The actual value of n does not change hugely.
- Slow light derives from large value of $dn/d\omega$
- So if n's total variations limited to order unity, then $dn/d\omega$ can only be significant over range of frequencies / $(dn/d\omega)^{-1}$