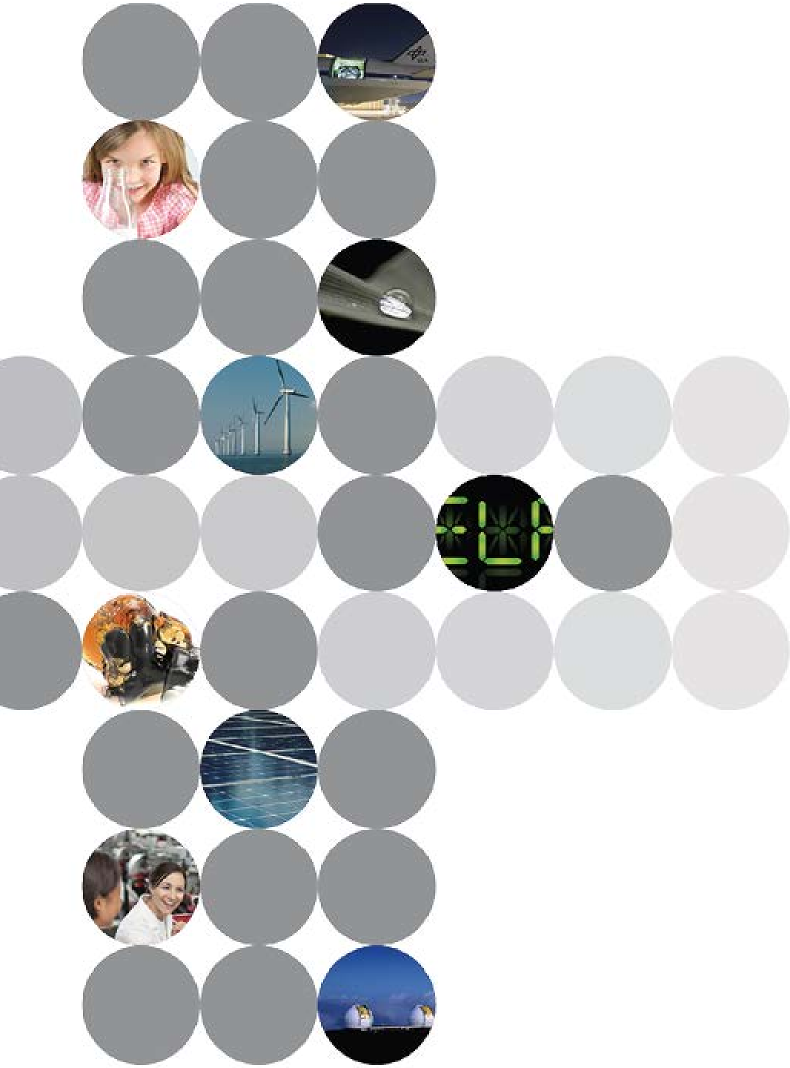
Journée thématique sur le bruit et les lasers femtosecondes



CSEM

technologies
that make the difference

Technologies lasers bas bruits et sources de bruit

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18.01.2018

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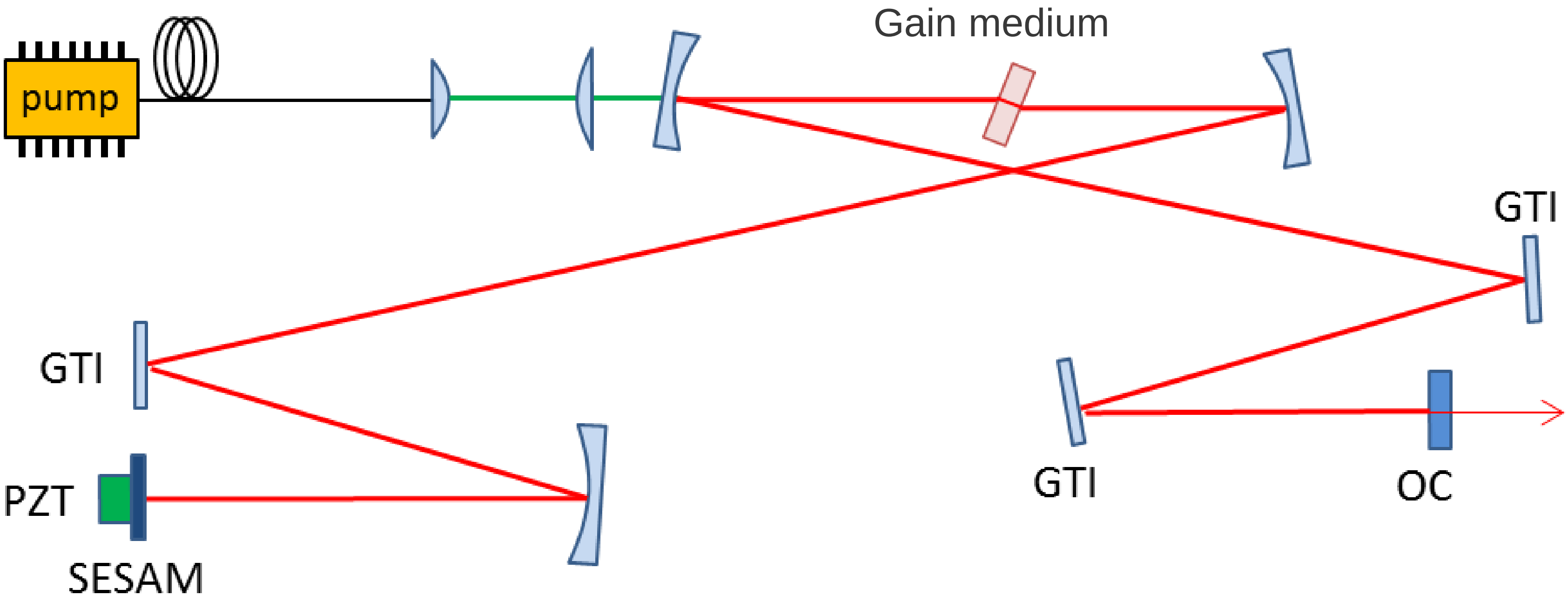
Outline

- Mode-locked lasers as low-noise oscillators
- Amplitude, CEO phase, optical phase, and timing jitter noise
- Elastic tape model & frequency dependance on gain and loss perturbations
- Noise sources (vibration, thermal & acoustics, pump RIN, quantum noise, dispersion, slow saturable absorber, self-steepening and Kramers-Kronig)
- Results (RIN, pulse jitter and microwave generation)
- Stabilization techniques for fceo and frep
- Summary and conclusions

Mode-locked laser based on DPSSL technology

- Diode-pumped solid-state laser - DPSSL



Output of a modelocked femtosecond laser

Time domain

Frequency domain

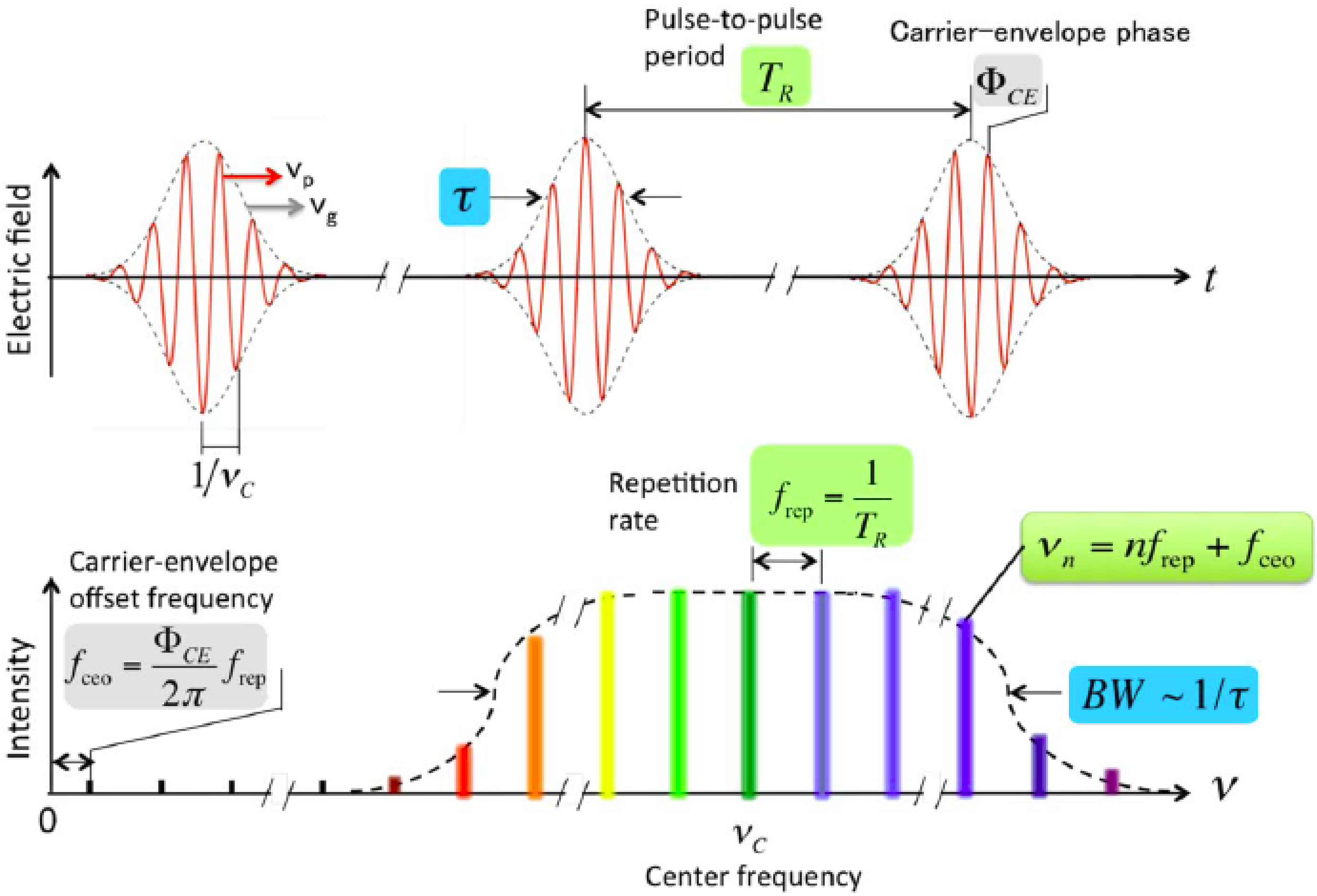
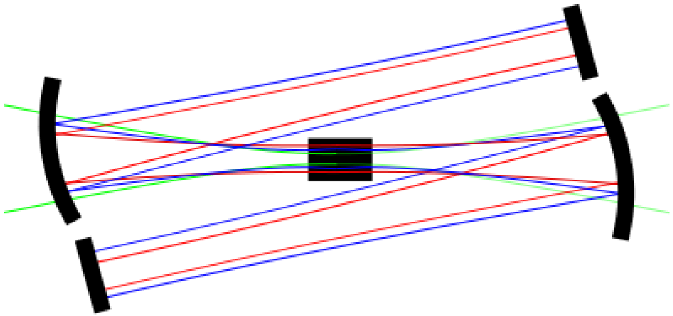
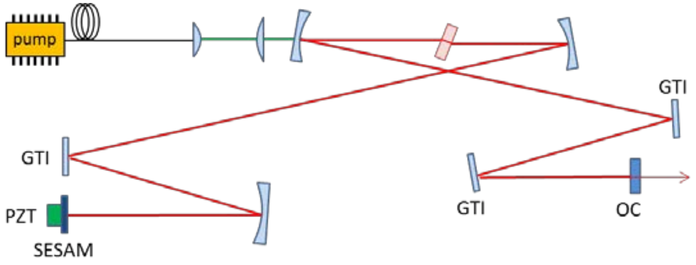


Figure from J. Kim and Y. Song, Adv. In Opt. And Phot. 8 465-540, 2016

Passive modelocking of solid-state lasers

- Kerr lens and saturable absorber



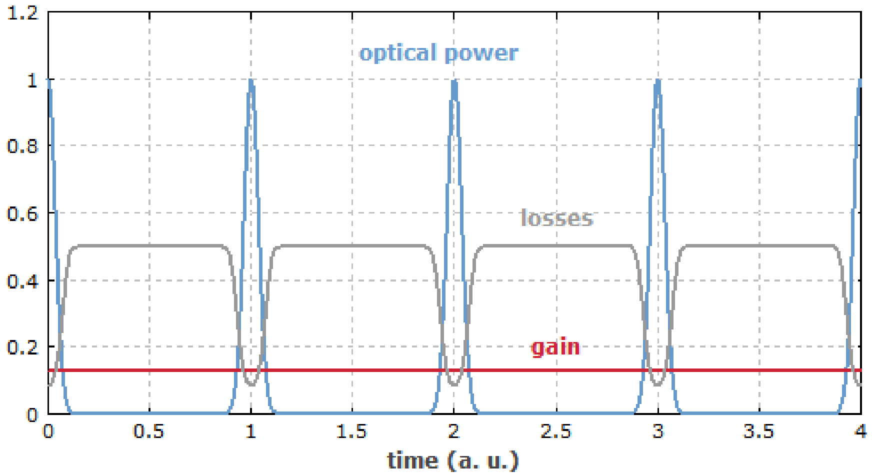


Parameter	Kerr lens	Saturable absorber
Recovery time	Fast (instantaneous)	«Slow»
Self-starting ML	Usually not	Yes
Wrt noise	Best case	The faster the better
Laser type	Ti:sapphire typically	Any type

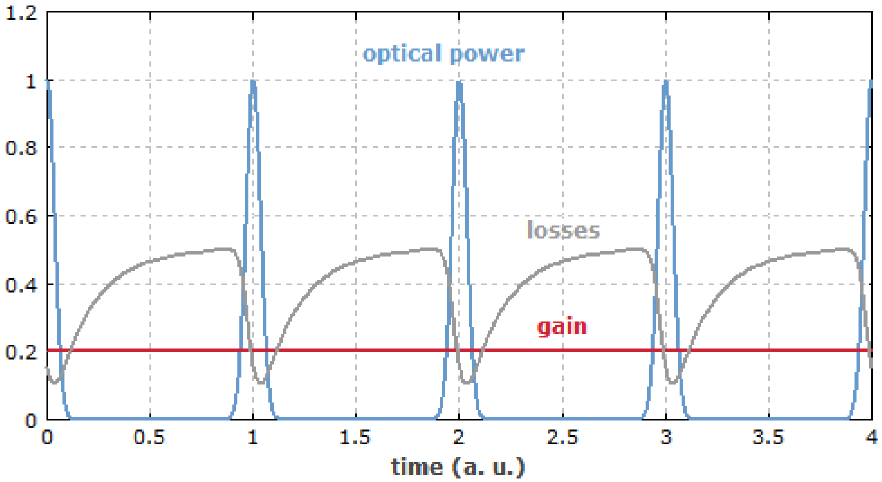
Left figure from wikipedia

Dynamics in solid-state laser vs. absorber speed

- Fast saturable absorber

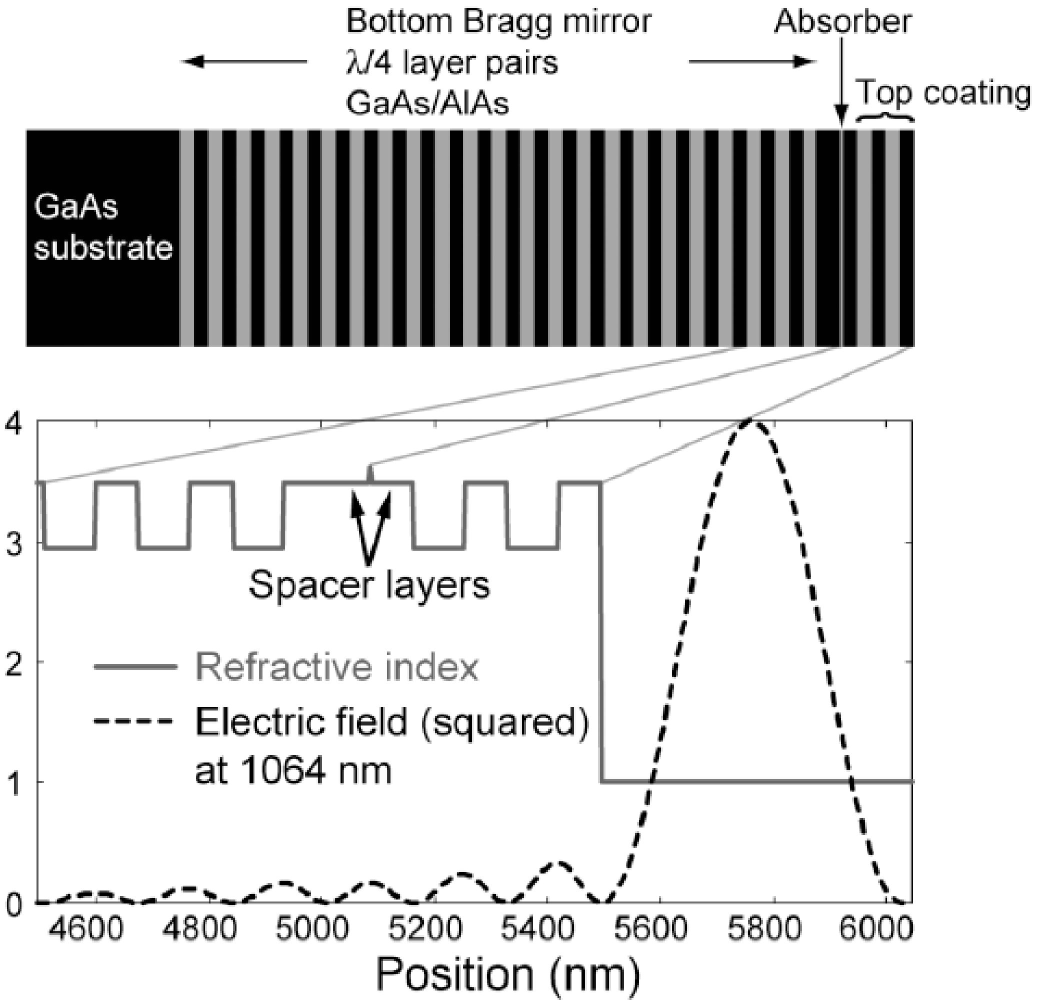


- Slow saturable absorber



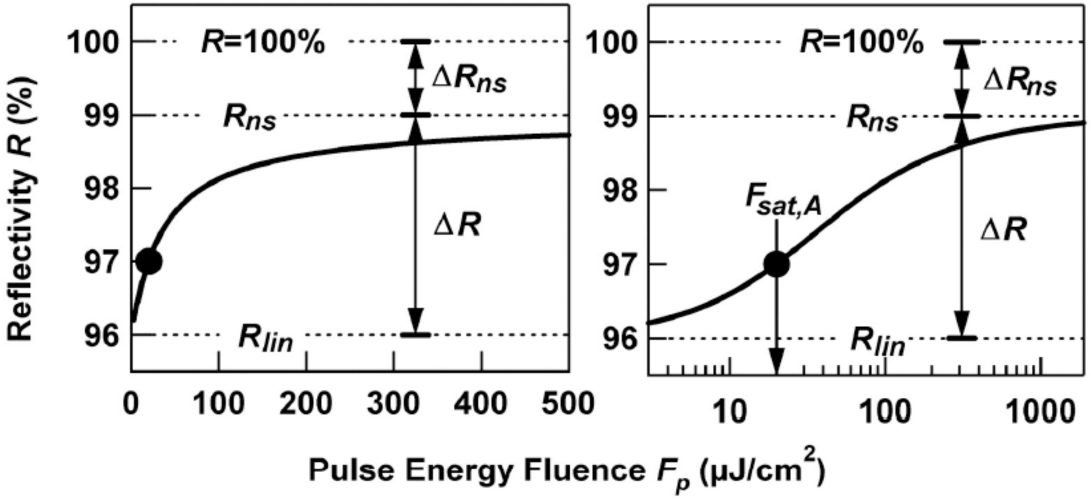
Figures from www.rp-photonics.com

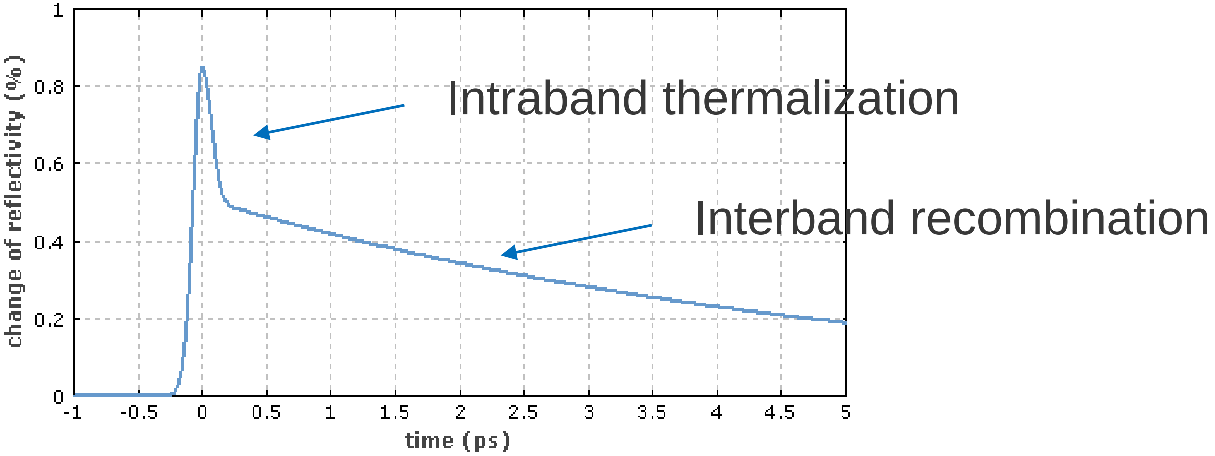
Passive mode-locking with Semiconductor Saturable Absorber Mirror (SESAM)



Figures from S. Lecomte, PhD thesis

Passive mode-locking with Semiconductor Saturable Absorber Mirror (SESAM)





Figures from S. Lecomte, PhD thesis and www.rp-photonics.com

Relevant laser parameters wrt noise

- Amplitude – RIN (Relative Intensity Noise)
- Pulse train timing jitter
- Optical phase of the comb modes
- Carrier-enveloppe offset phase noise

$$A(t) = [A_0 + \Delta A_0(t)] \sum_{m=-\infty}^{+\infty} a(t - mT_R + \Delta T_R(t)) \exp[j\{2\pi\nu_c t + m\Phi_{\mathrm{CE}} + \Delta\theta(t)\}]$$

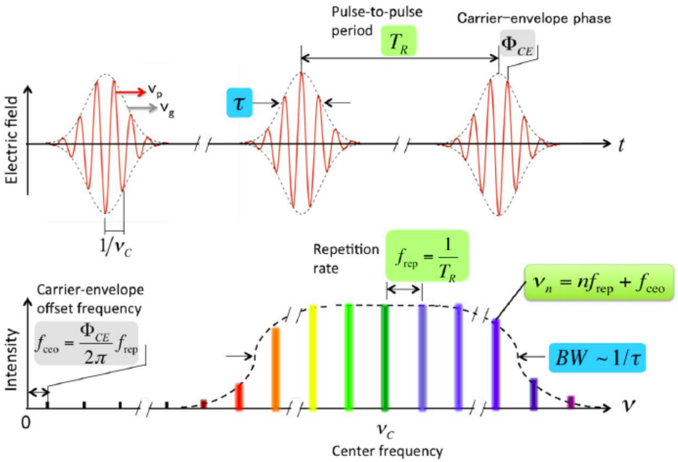
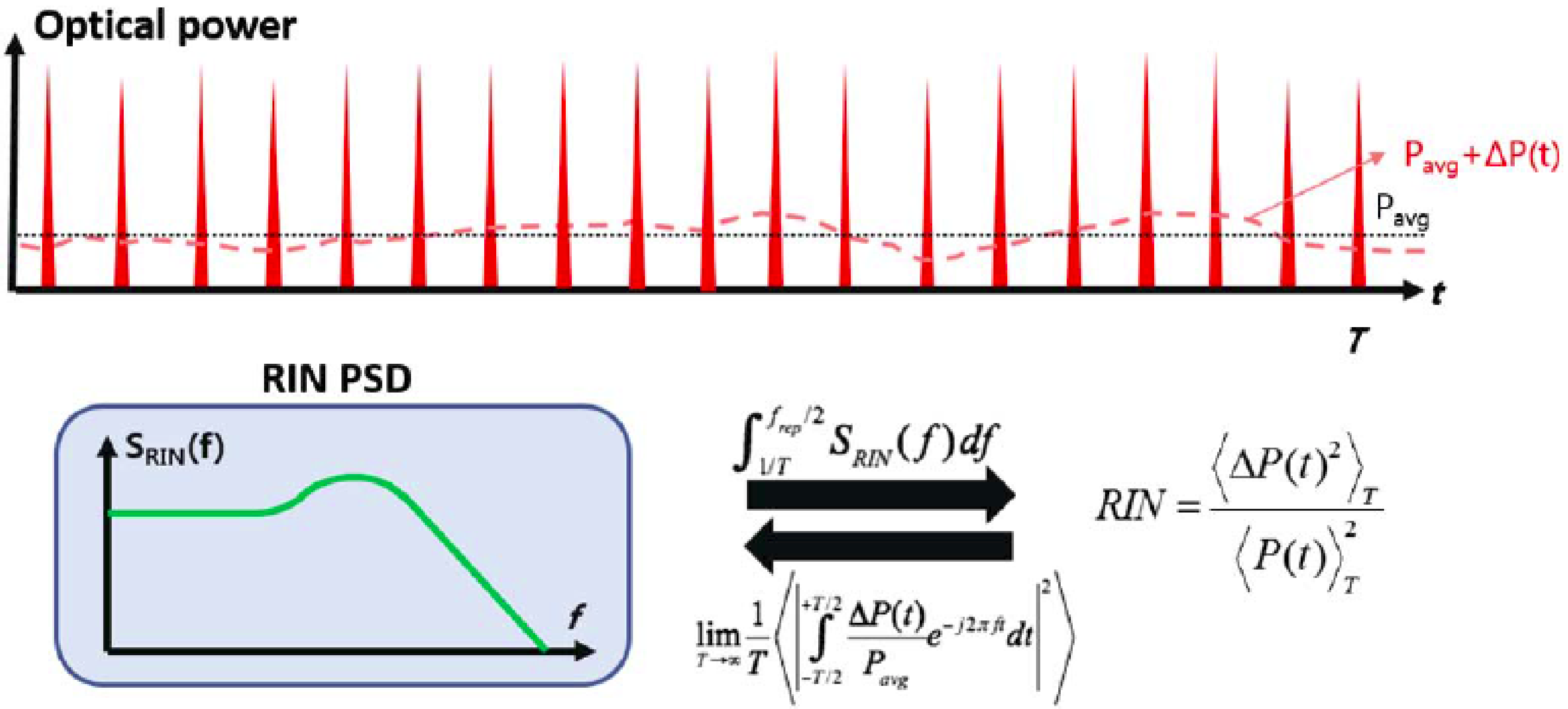


Figure from J. Kim and Y. Song, Adv. In Opt. And Phot. 8 465-540, 2016

Amplitude noise - RIN



$$\int_{1/T}^{f_{rep}/2} S_{RIN}(f)\,df$$

$$\lim_{T\to\infty}\frac{1}{T}\left\langle\left|\int_{-T/2}^{+T/2}\frac{\Delta P(t)}{P_{avg}}e^{-j2\pi ft}\,dt\right|^2\right\rangle$$

$$RIN=\frac{\left\langle \Delta P(t)^2\right\rangle_T}{\left\langle P(t)\right\rangle_T^2}$$

Quantum limit: $S_{\mathrm{RIN}}^{\text{shot noise}}(f)=\frac{2h\nu_c}{P_{\mathrm{avg}}}$

Figure from J. Kim and Y. Song, Adv. In Opt. And Phot. 8 465-540, 2016

Pulse train timing jitter

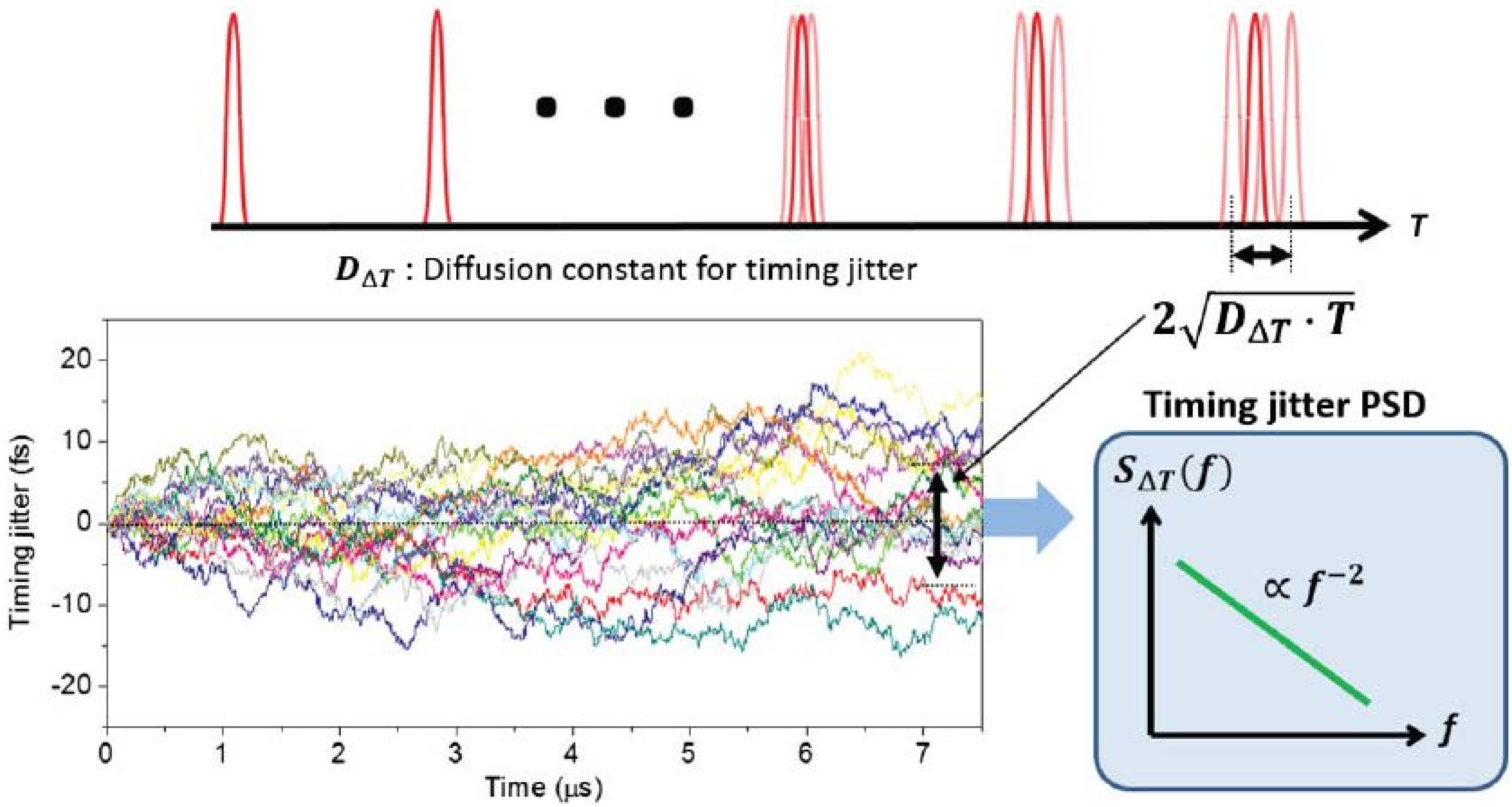


Figure from J. Kim and Y. Song, Adv. In Opt. And Phot. 8 465-540, 2016

Optical phase (comb-mode linewidth)

In case of ASE quantum limit and uncorrelatead noise:

$$\Delta\nu_n = \Delta\nu_{\Delta\theta} + [2\pi\tau(\nu_n - \nu_c)]^2 \Delta\nu_{\Delta T}$$

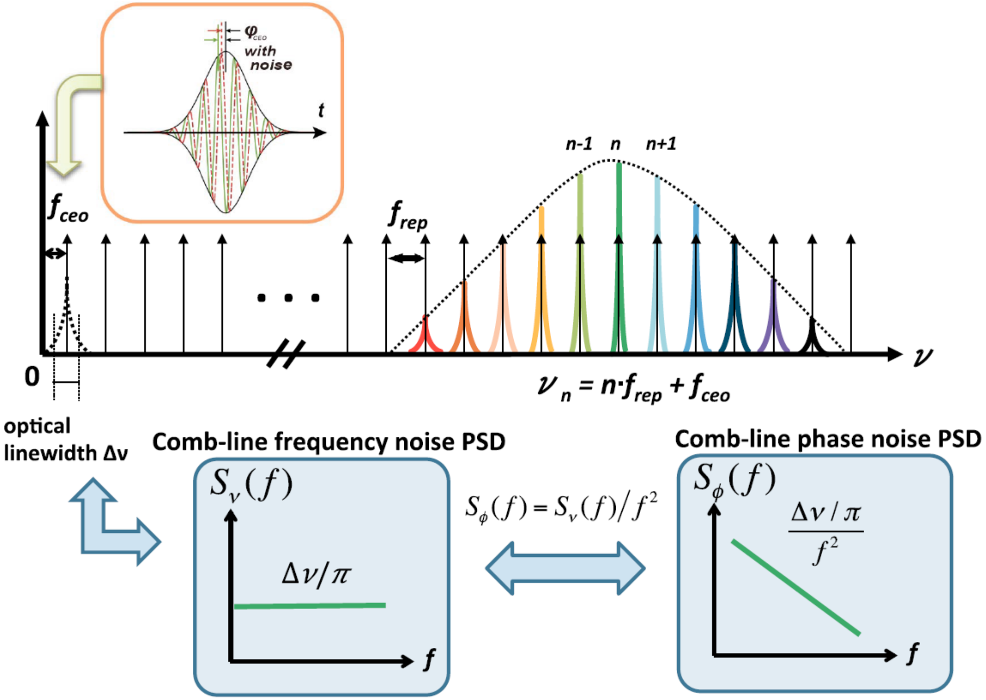
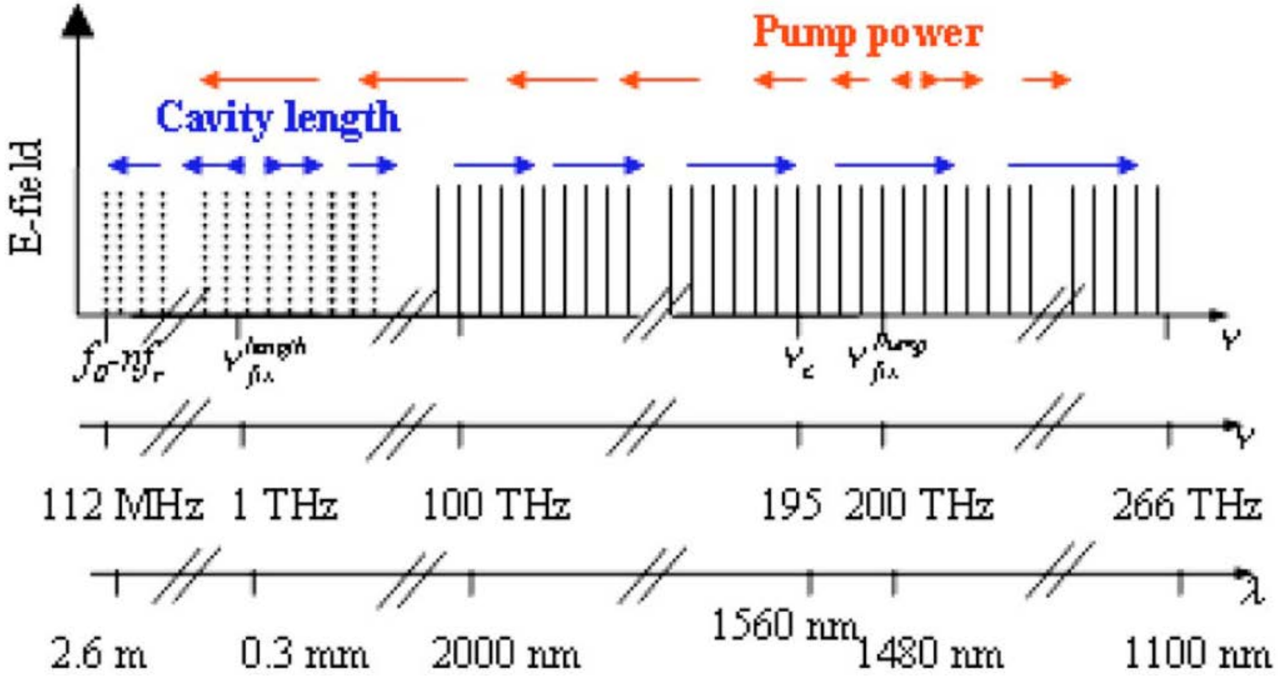


Figure from J. Kim and Y. Song, Adv. In Opt. And Phot. 8 465-540, 2016

Elastic tape model

- Influence of noise sources depends on fix frequency (of the perturbation) and on considered comb mode of interest



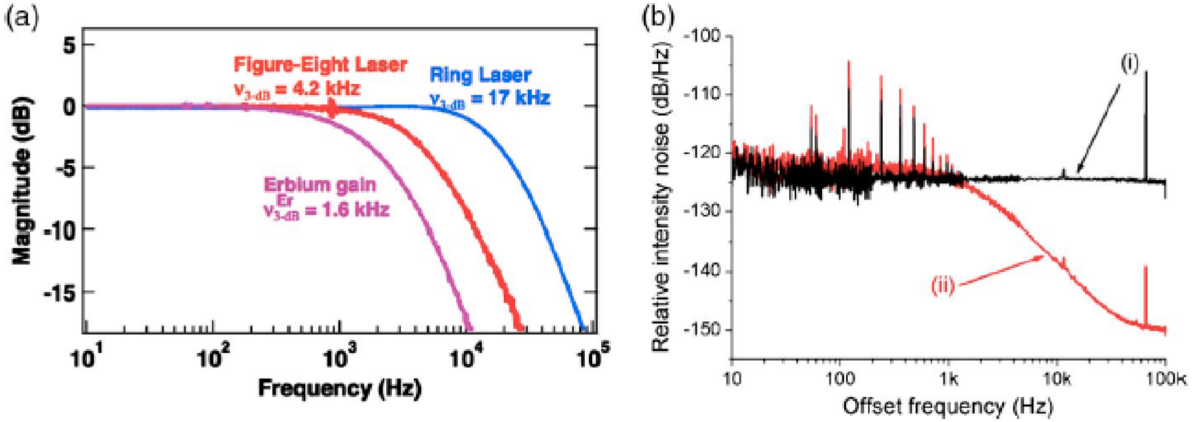
From N. R. Newbury and W. C. Swann, JOSA B 24 1756-1771, 2007

Elastic tape model – frequency dependance

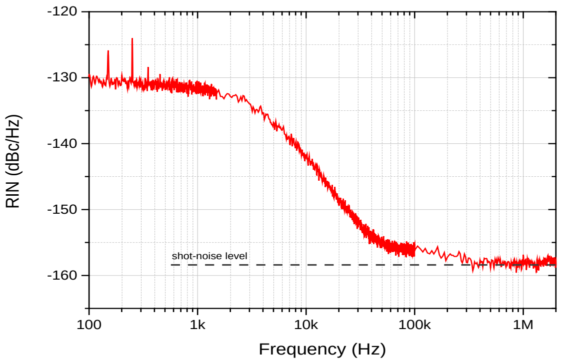
- Frequency dependance is defined by the physics of the laser

  - Gain modulation bandwidth: $\omega_1 \approx T_G^{-1}\left(\frac{\partial q}{\partial E_p} E_p\right)^{-1}$
  - Loss modulation bandwidth: $\omega_2 \approx T_R^{-1}\left(\frac{\partial q}{\partial E_p} E_p\right)^{-1}$

$\omega_2 >> \omega_1$



RIN 100MHz DPSSL



From C.-C. Lee et al. Opt. Lett. 37, 3084-3086, 2012 and from J. Kim and Y. Song, Adv. In Opt. And Phot. 8 465-540, 2016

Elastic tape model

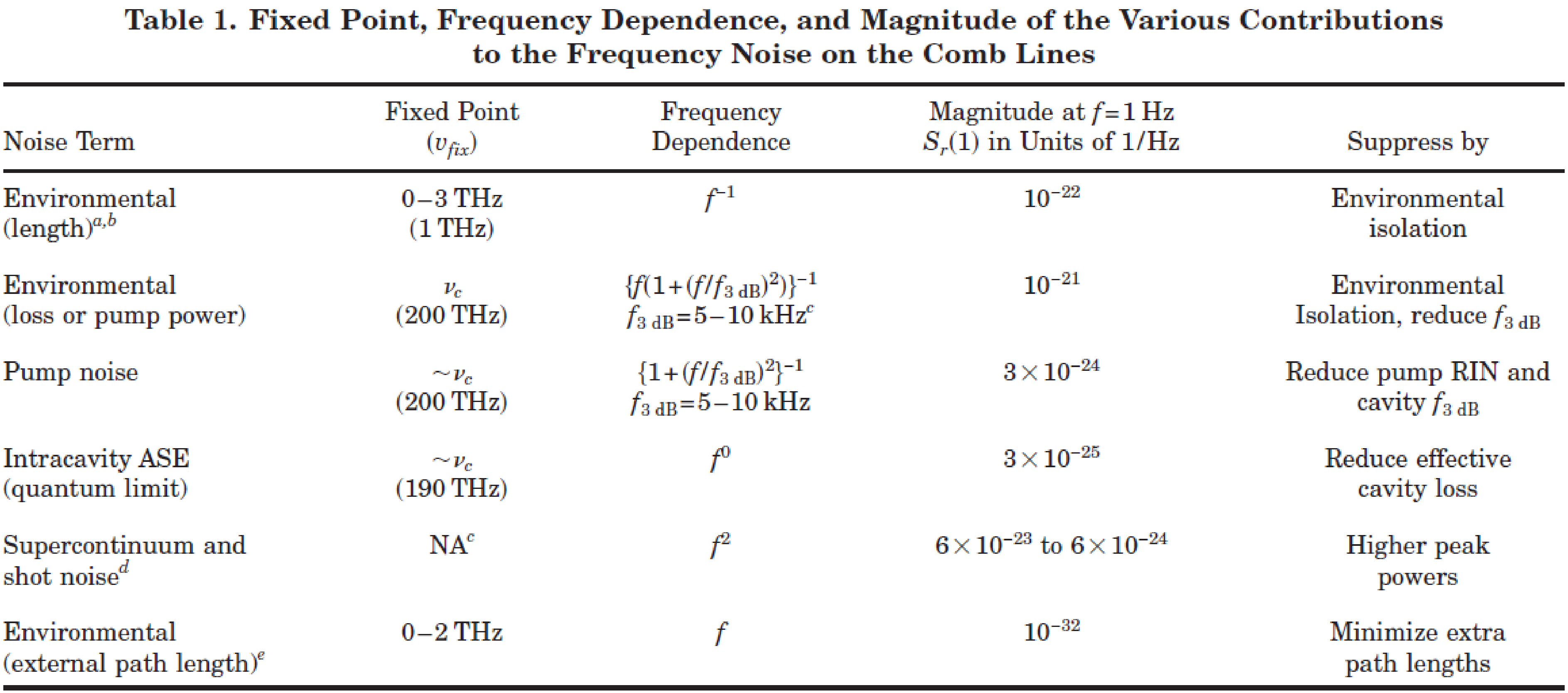


Table 1. Fixed Point, Frequency Dependence, and Magnitude of the Various Contributions to the Frequency Noise on the Comb Lines

Noise Term	Fixed Point (v_{fix})	Frequency Dependence	Magnitude at $f=1$ Hz $S_r(1)$ in Units of 1/Hz	Suppress by
Environmental (length)[a,b]	0–3 THz (1 THz)	f^{-1}	10^{-22}	Environmental isolation
Environmental (loss or pump power)	ν_c (200 THz)	$\{f(1+(f/f_{3\,\mathrm{dB}})^2)\}^{-1}$ $f_{3\,\mathrm{dB}}=5-10$ kHz[c]	10^{-21}	Environmental Isolation, reduce $f_{3\,\mathrm{dB}}$
Pump noise	$\sim\nu_c$ (200 THz)	$\{1+(f/f_{3\,\mathrm{dB}})^2\}^{-1}$ $f_{3\,\mathrm{dB}}=5-10$ kHz	3×10^{-24}	Reduce pump RIN and cavity $f_{3\,\mathrm{dB}}$
Intracavity ASE (quantum limit)	$\sim\nu_c$ (190 THz)	f^0	3×10^{-25}	Reduce effective cavity loss
Supercontinuum and shot noise[d]	NA[c]	f^2	6×10^{-23} to 6×10^{-24}	Higher peak powers
Environmental (external path length)[e]	0–2 THz	f	10^{-32}	Minimize extra path lengths

From N. R. Newbury and W. C. Swann, JOSA B 24 1756-1771, 2007

Comb-line frequency noise

Effect	Frequency noise Power Spectral Density (Hz²/Hz)	Physical cause
Quantum noise (QL)	$S_{\nu}^{\mathrm{ST}} = \frac{\Theta h \nu_c l_{\mathrm{tot}}}{8\pi^2 P_{\mathrm{int}}} \cdot f_{\mathrm{rep}}^2$	Contribution of losses and gain to comb-line
ASE induced timing drift	$S_{\nu,n}^{\mathrm{ASE}}(f) = S_{\nu}^{\mathrm{ST}} + (\nu_n - \nu_c)^2 \cdot S_{f_{\mathrm{rep}}}^{\mathrm{ASE}}(f)/f_{\mathrm{rep}}^2$	For any comb line n
Pump RIN induced*	$S_{\nu,n}^{\mathrm{Pump}} = (n - n_{\mathrm{fix}}^{\mathrm{Pump}})^2 S_{f_{\mathrm{rep}}}^{\mathrm{Pump}}$	
Length jitter induced	$\nu_{\mathrm{fix}}^{\mathrm{length}} = \nu_c (1 - v_g^L / v_p^L)$	

*: $\frac{df_{\mathrm{ceo}}}{dP} = \frac{\beta_0}{2\pi}\left(\frac{df_{\mathrm{rep}}}{dP}\right) + \frac{f_{\mathrm{rep}}}{2\pi}\left(\frac{d\phi_0}{dP}\right)$ & $n_{\mathrm{fix}}^{\mathrm{Pump}} \equiv -(df_{\mathrm{ceo}}/dP)/(df_{\mathrm{rep}}/dP)$

$$S_{f_{\mathrm{rep}}}^{\mathrm{ASE}}(f) = (2\pi f_{\mathrm{rep}})^2 f^2 S_{\Delta T}^{\mathrm{ASE}}(f)$$

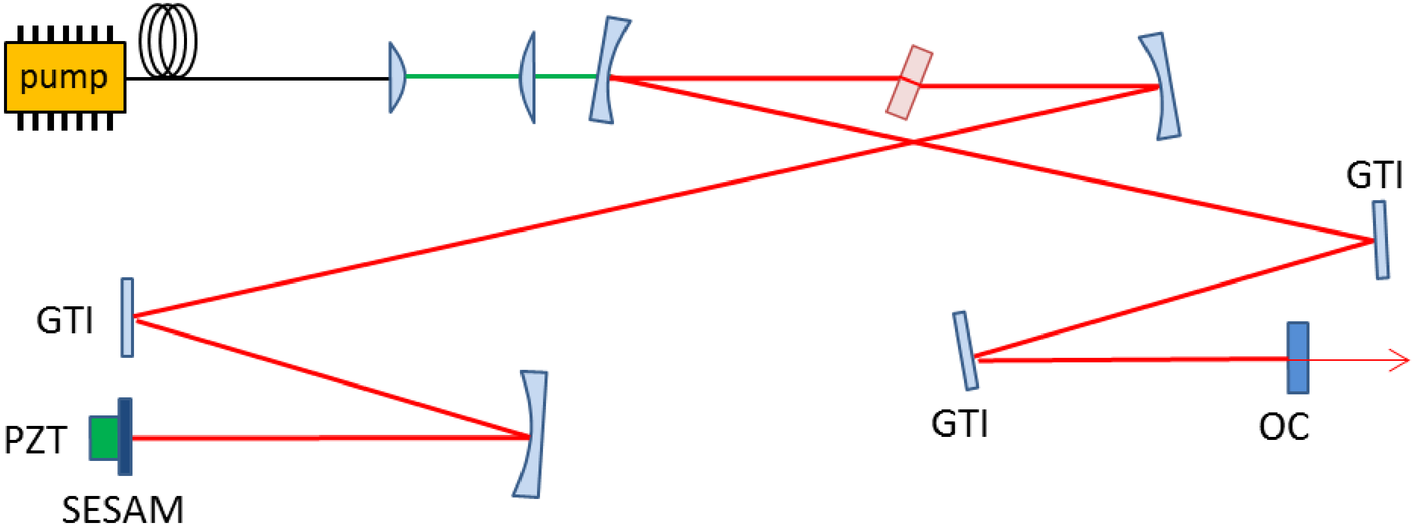
From J. Kim and Y. Song, Adv. In Opt. And Phot. 8 465-540, 2016

Timing jitter

Effect	Jitter Power Spectral Density (fs²/Hz)	Physical cause
Quantum noise (QL)	$S_{\Delta t}^{QL}(f) = 0.5294 \frac{1}{(2\pi f)^2} \frac{h\nu_0}{E_p} \frac{g}{T_{rt}} \tau_p^2$	Contribution of losses and gain to timing jitter. Fundamental quantum limit, no dispersion is considered.
Gordon-Haus (G-H)	$S_{\Delta t}^{G-H}(f) = \left(\frac{D_2}{f T_{rt}}\right)^2 \frac{g}{T_{rt}\tau_p^2} \frac{0.21}{(2\pi f)^2 + \left(0.21 \frac{g}{T_{rt}} \frac{1}{\tau_p^2 \Delta f_g^2}\right)^2}$	Pulse center optical frequency fluctuation due to quantum noise coupled to intracavity dispersion
Kramers-Kronig (K-K)	$S_{\Delta t}^{K-K}(f) = \left(\frac{1}{2\pi \Delta f_g}\right)^2 \left[1 + \left(\frac{E_p \Delta R}{2\pi f T_{rt}}\right)^2\right] S_I(f)$	Coupling of variation of refractive index through inversion level and pump power fluctuations
Self-steepening (S-S)	$S_{\Delta t}^{S-S}(f) = \left(\frac{\Delta\varphi_{nl}}{2\pi^2 f T_{rt} \nu_0}\right)^2 S_I(f)$	Phase shift (timing jitter) caused by nonlinear refractive index (intensity dependant)
Slow-saturable absorber (SSA)	$S_{\Delta t}^{SSA}(f) = \left(\frac{s d\Delta t/ds}{2\pi f T_{rt}}\right)^2 S_I(f)$	Temporal shift induced by the fact that the leading part of the pulse is more attenuated by the saturable absorber than the trailing part
Total	$S_{\Delta t}^{tot} = \sum_i S_{\Delta t}^{i}$	i stands for the supra-indexes corresponding to all the physical effects above

Equations from R. Paschotta, Appl. Phys. B, 79 163-173, 2004

Why DPSSL is low noise?



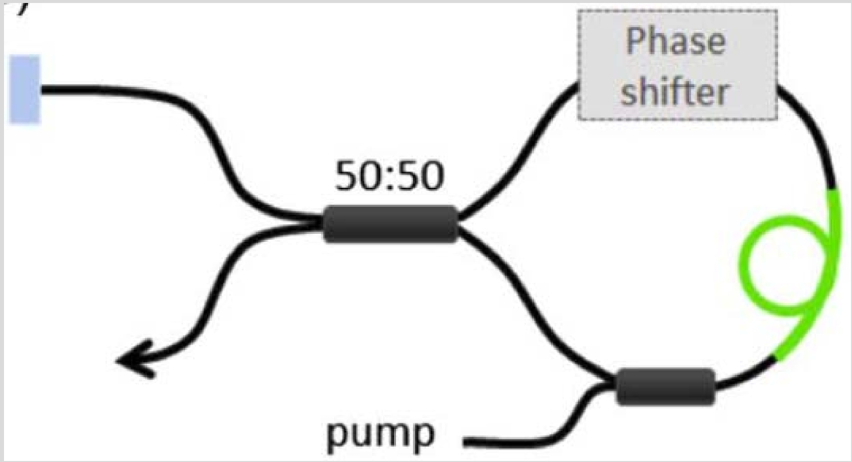
- **Low gain**
- **Large pulse energy**
- Typically producing solitons
- Typical repetition rates: 40 MHz – 1 GHz

→ **Low quantum noise**

And fiber lasers?

- Large number of different architectures
- Best performances obtained with nonlinear amplifiying loop mirror (NALM) architecture thanks to instantaneous saturable absorber (Kerr lens like)

«Figure 9» design with NALM design

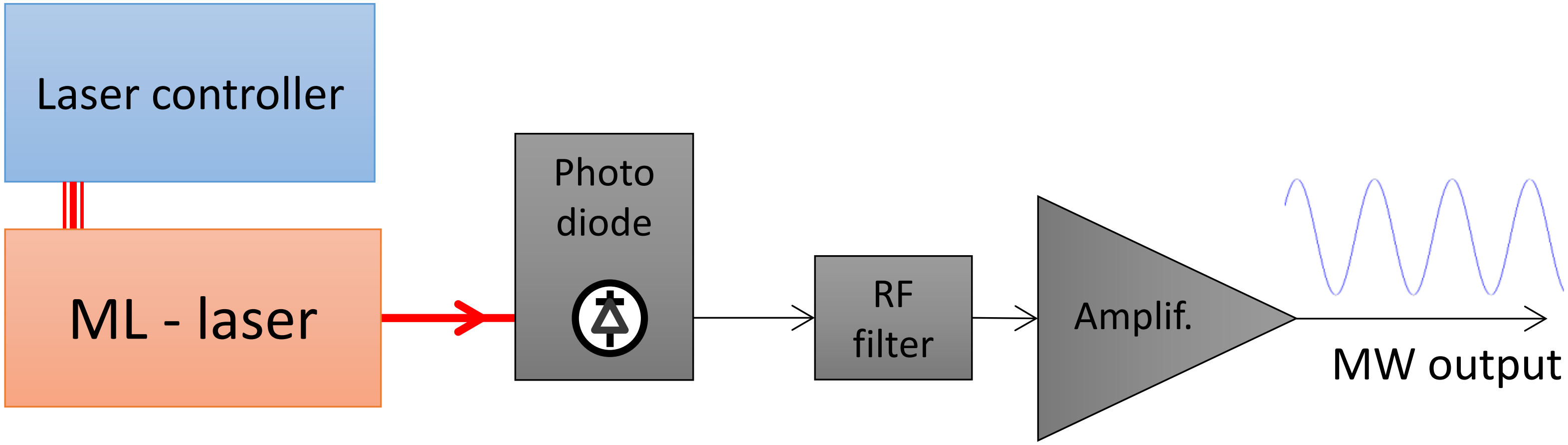


- Compact and robust design
- Limited pulse energy and relatively high intracavity losses
- Timing jitter larger than solid-state lasers

Figure from J. Kim and Y. Song, Adv. In Opt. And Phot. 8 465-540, 2016

Optical pulse timing jitter and microwave phase noise

Single sideband phase noise	$L(f) = 10\log\left(4\pi^2 f_c^2 S_{\Delta t}(f)\right),\ \ dBc/Hz$
Shot noise associated single sideband phase noise	$L_{SN}(f) = 10\log\left(\frac{q}{2\,I_{av}}\right),\ \ dBc/Hz$


Laser controller

ML - laser

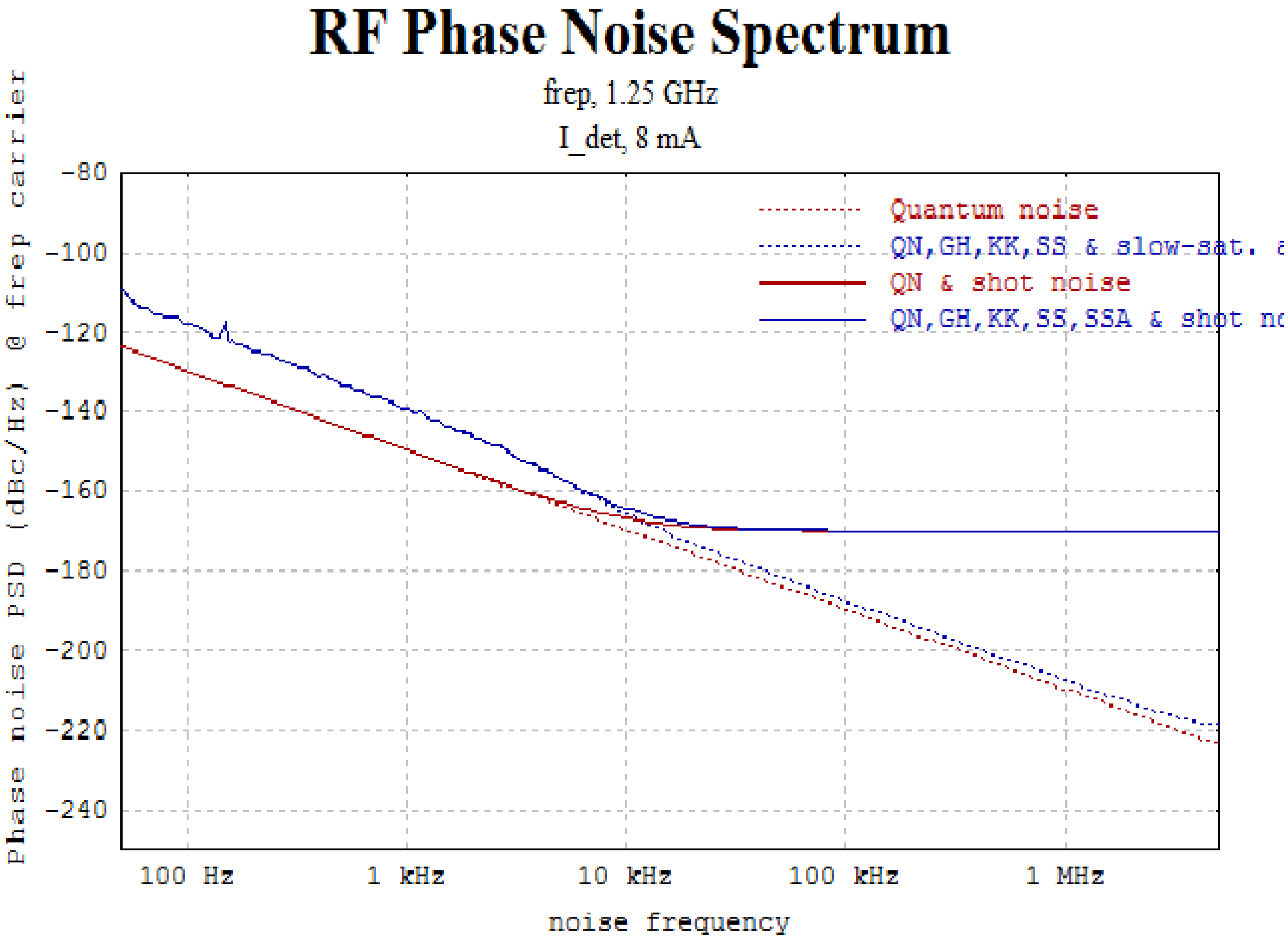
Photo diode

RF filter

Amplif.

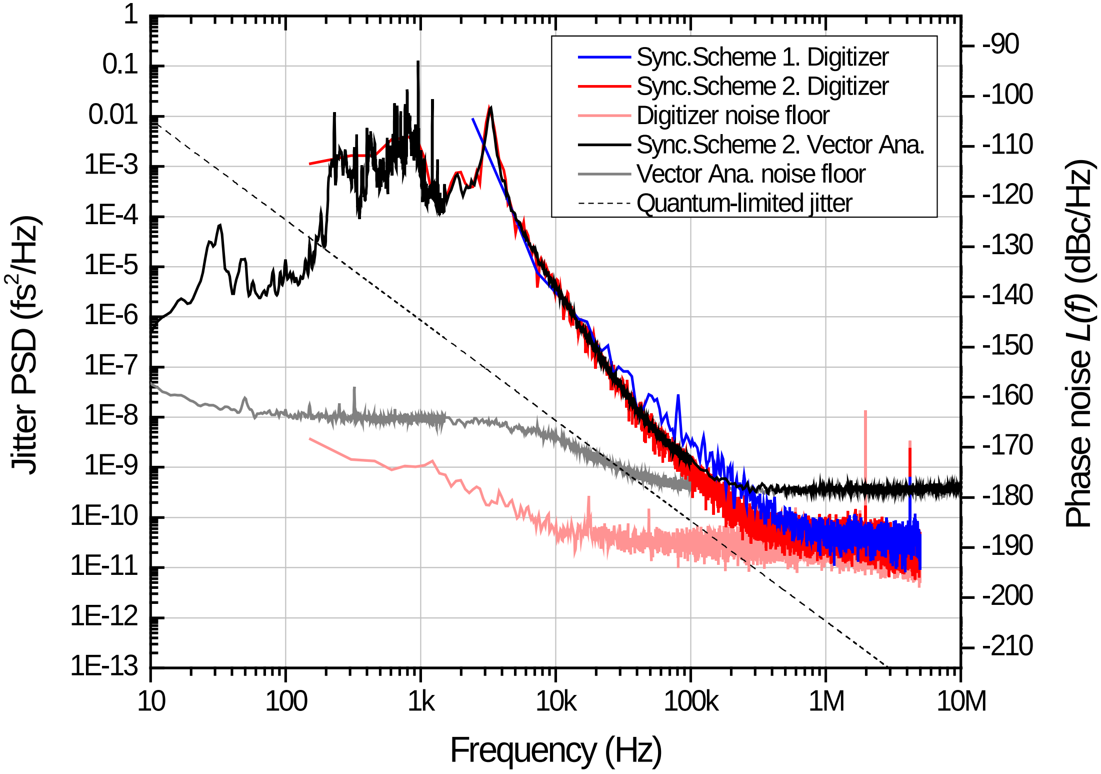
MW output

Timing jitter modelling



Timing jitter of DPSSL

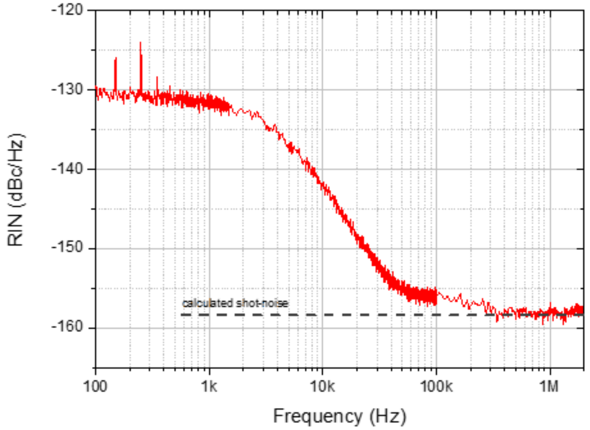
- Optical pulse train jitter of 100-MHz rep rate 1556 nm DPSSL
- Optical measurement (no optical-to-electrical conversion), 83 as (integrated from 10 kHz to 50 MHz)



E. Portuondo-Campa et al., Opt. Lett. 38, 2650-2653 (2013)

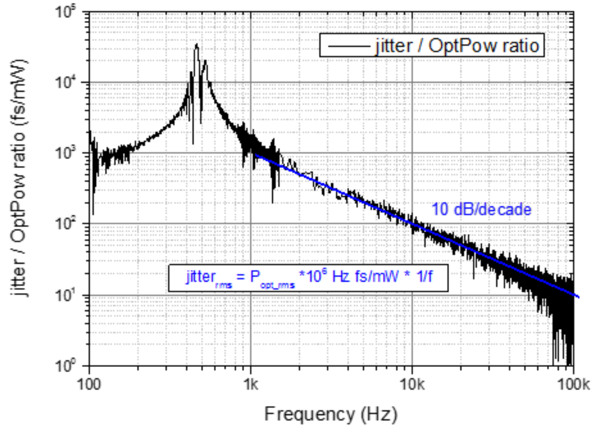
Investigation of extra-noise source

Measured Amplitude Noise



x

Measured AM to PM conversion



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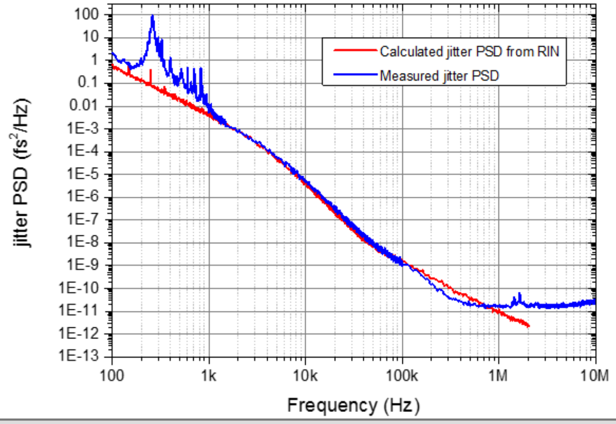
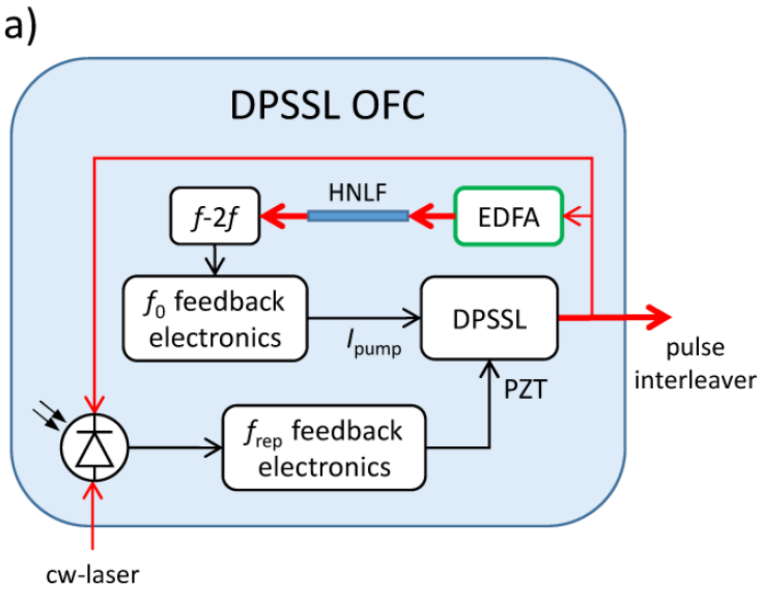
Calculated Jitter power spectral density

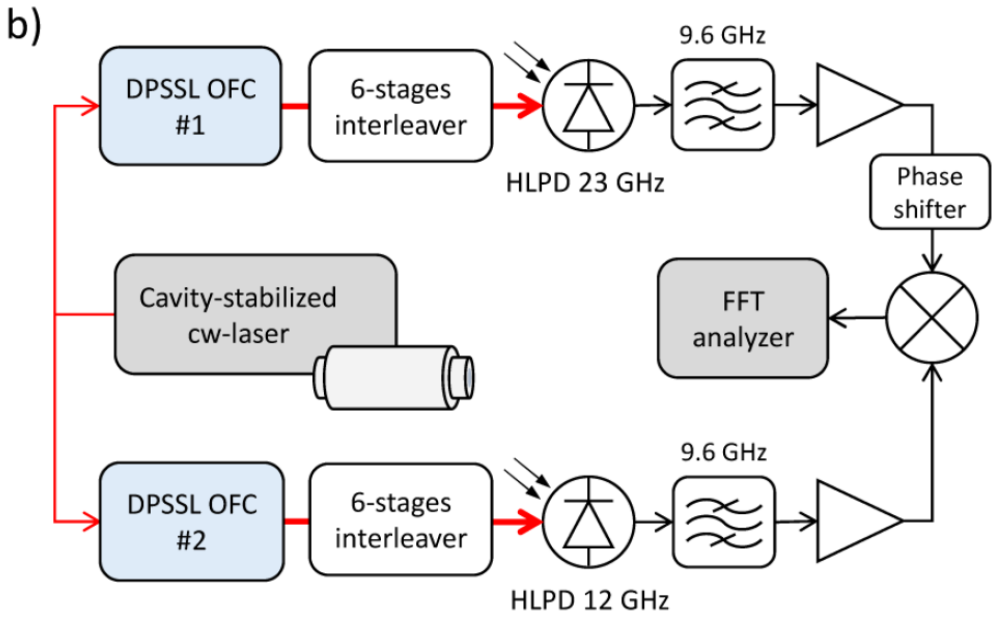
=



E. Portuondo-Campa et al., EFTF 2014

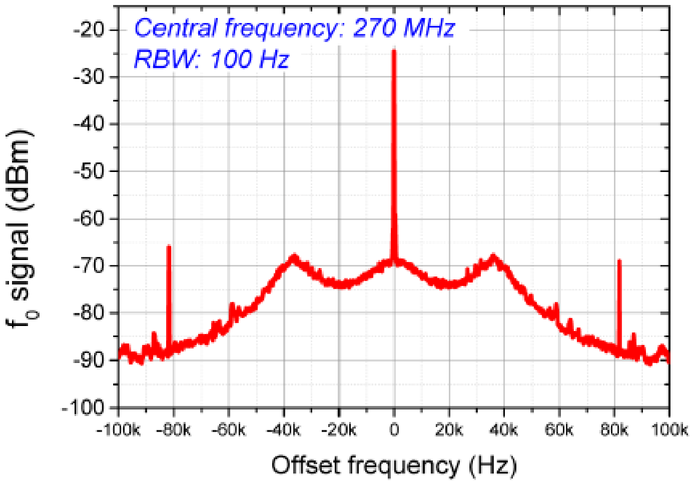
Ultrapure microwave generation

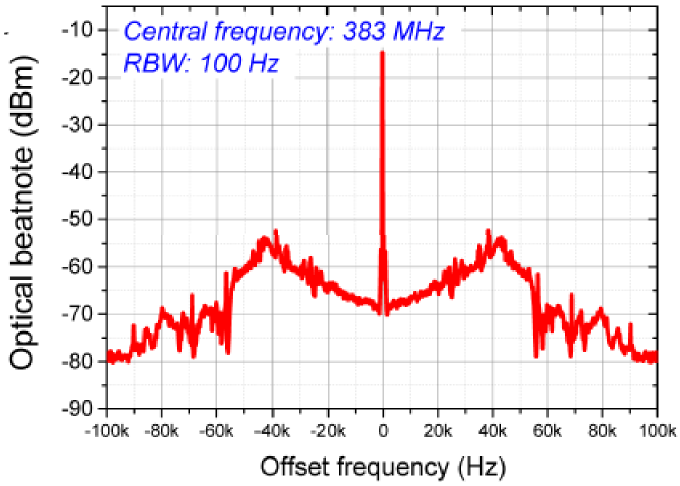


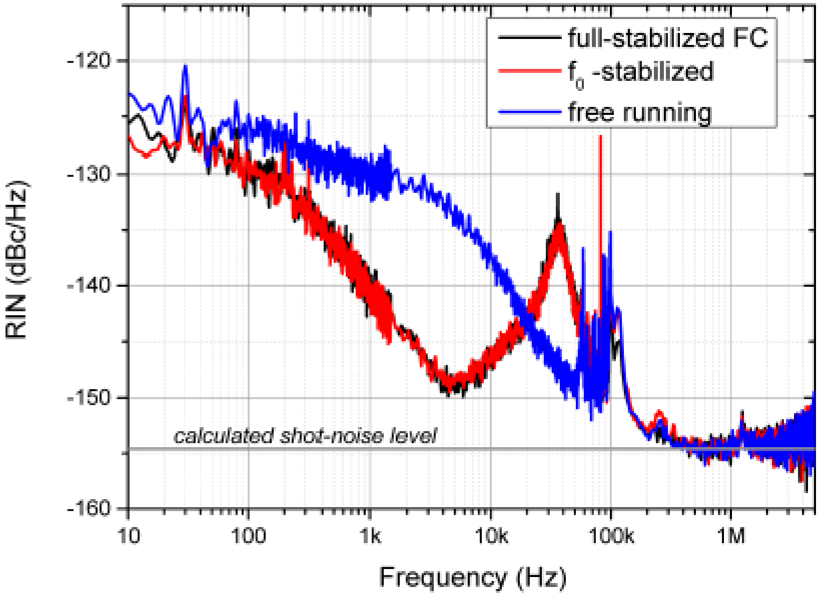


E. Portuondo-Campa *et al.*, Opt. Express 23, 32441-32451 (2015)

Stabilized 100MHz DPSSL comb

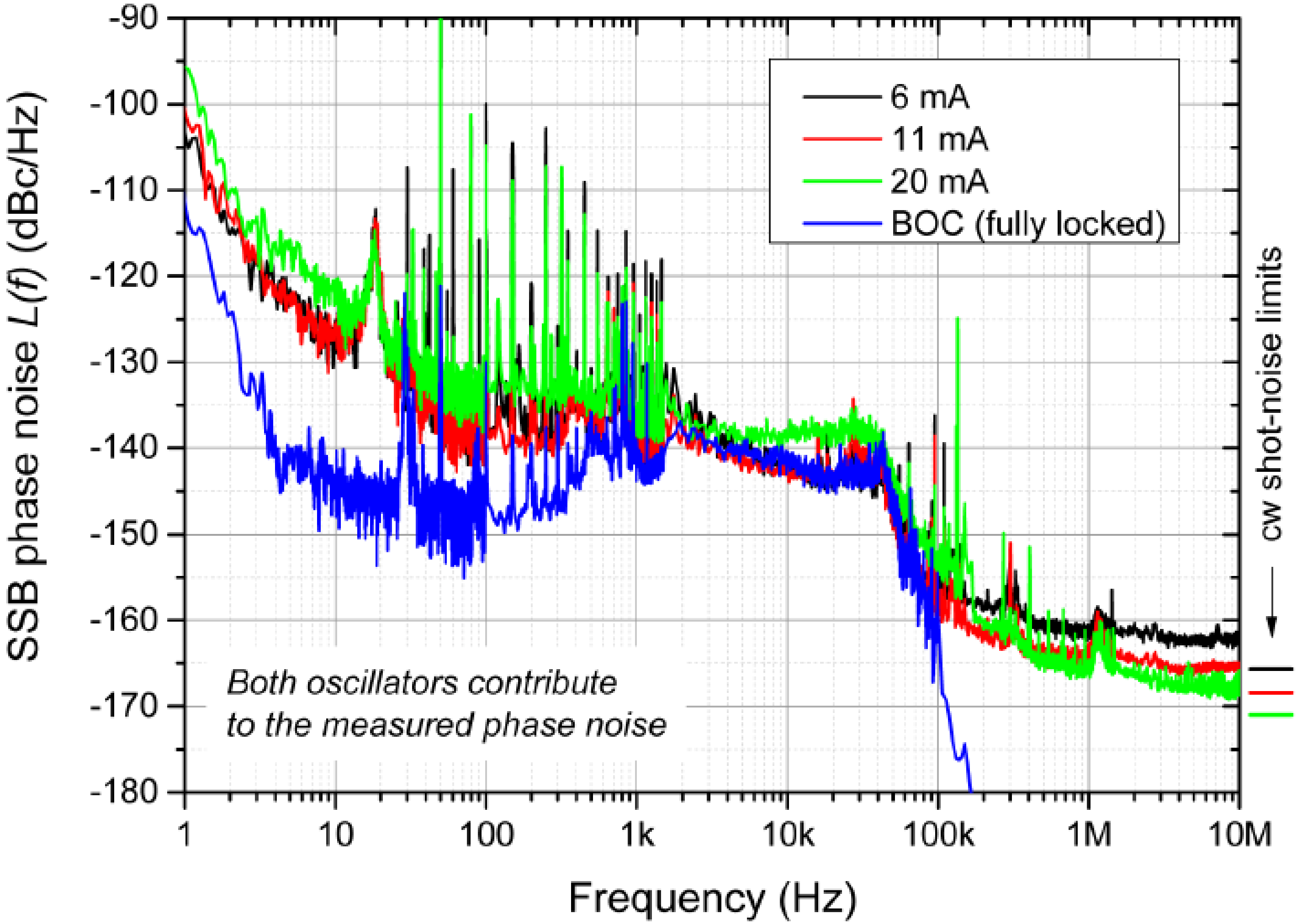






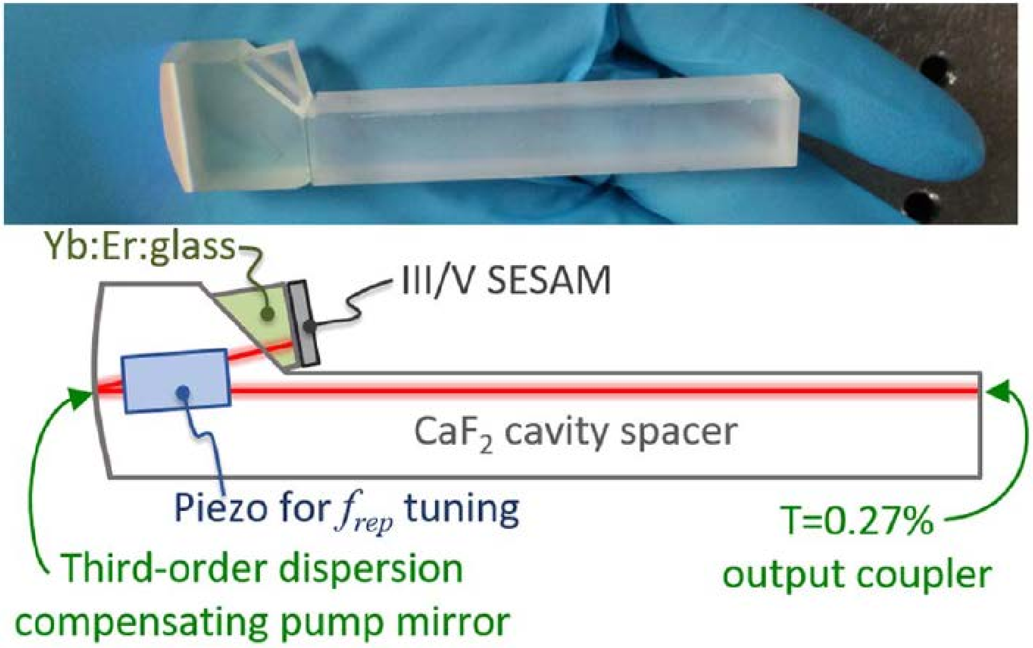
E. Portuondo-Campa *et al.*, Opt. Express 23, 32441-32451 (2015)

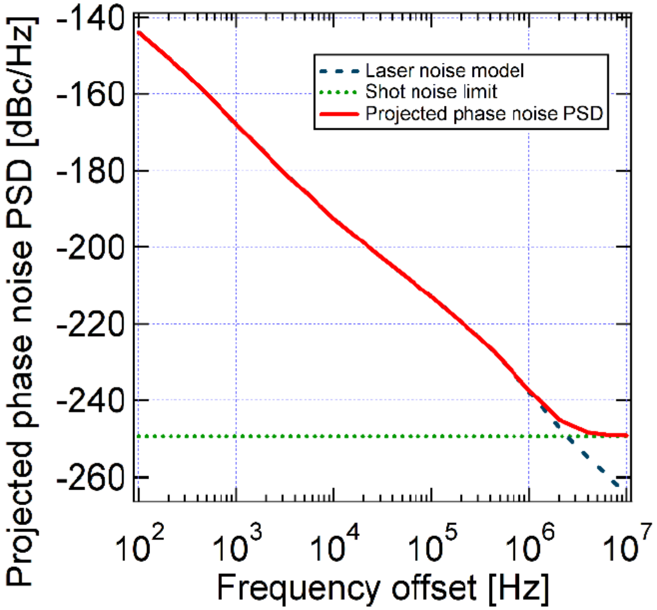
Microwave phase noise and pulse timing jitter



E. Portuondo-Campa *et al.*, Opt. Express 23, 32441-32451 (2015)

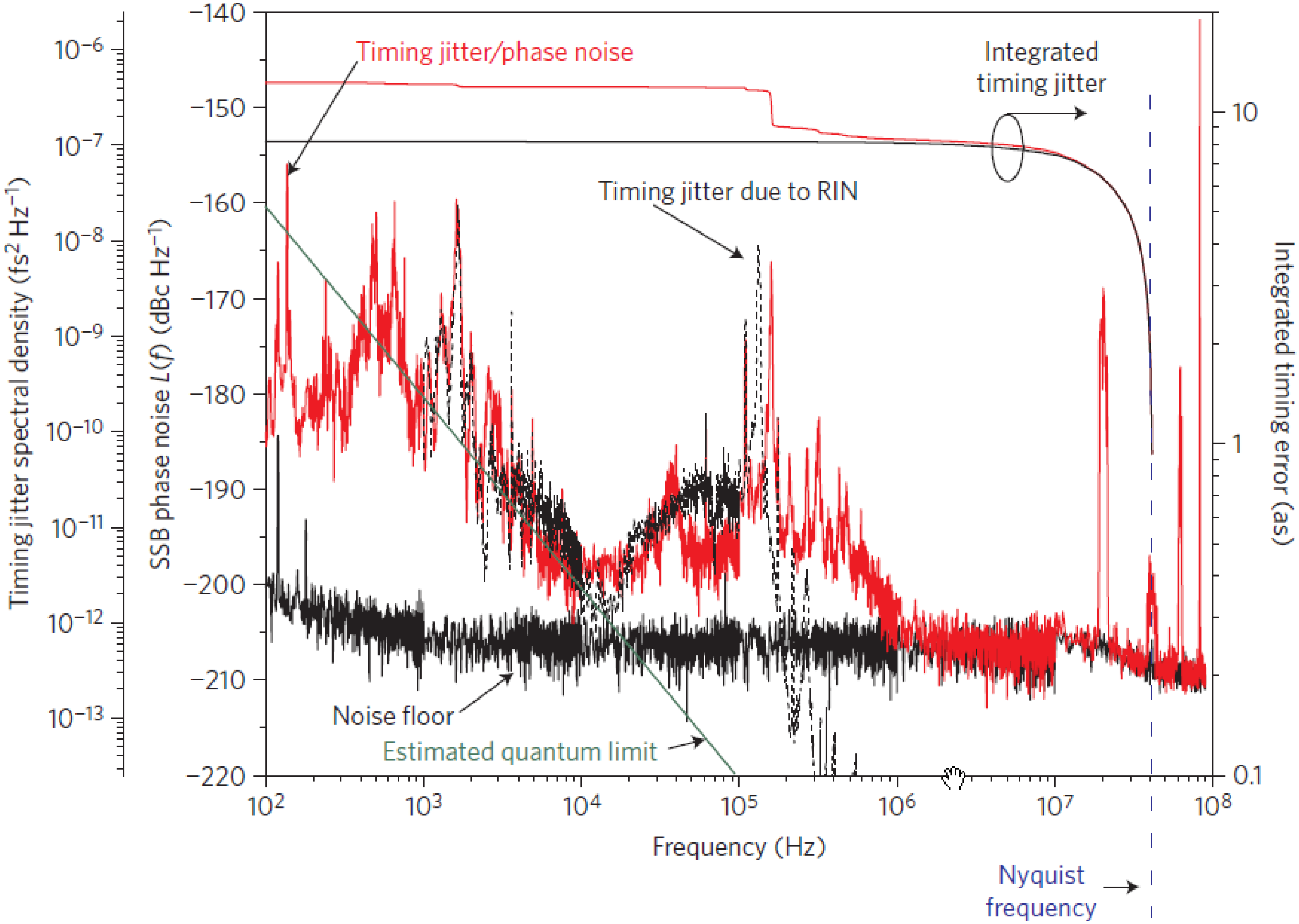
Ultralow noise 1GHz MLL based on monolithic design





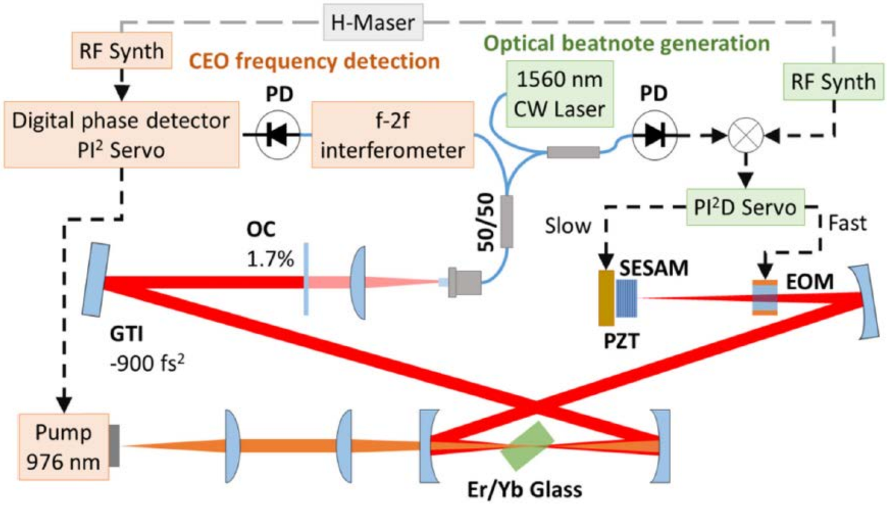
T. D. Shoji *et al.*, Optica 3, 995-998 (2016)

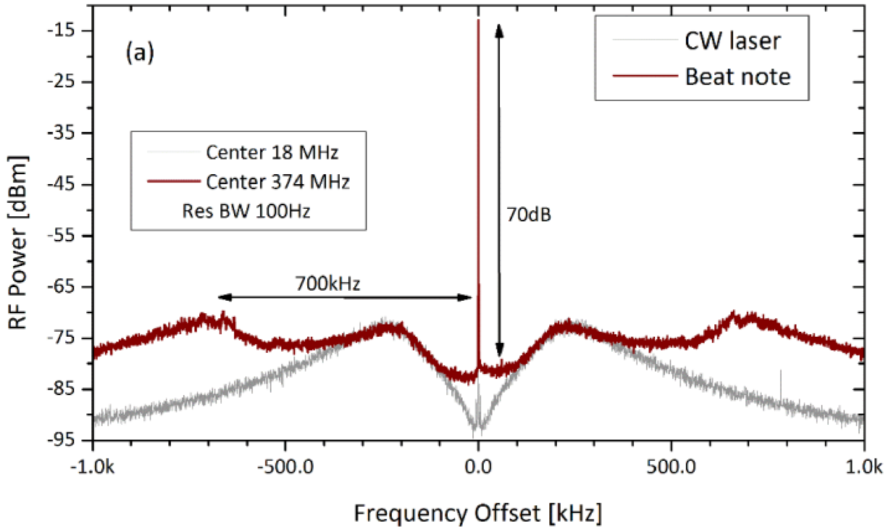
100MHz Kerr lens Titanium Sapphire pulse timing jitter



A. J. Benedick *et al.*, Nat. Phot. 6, 97-100 (2012)

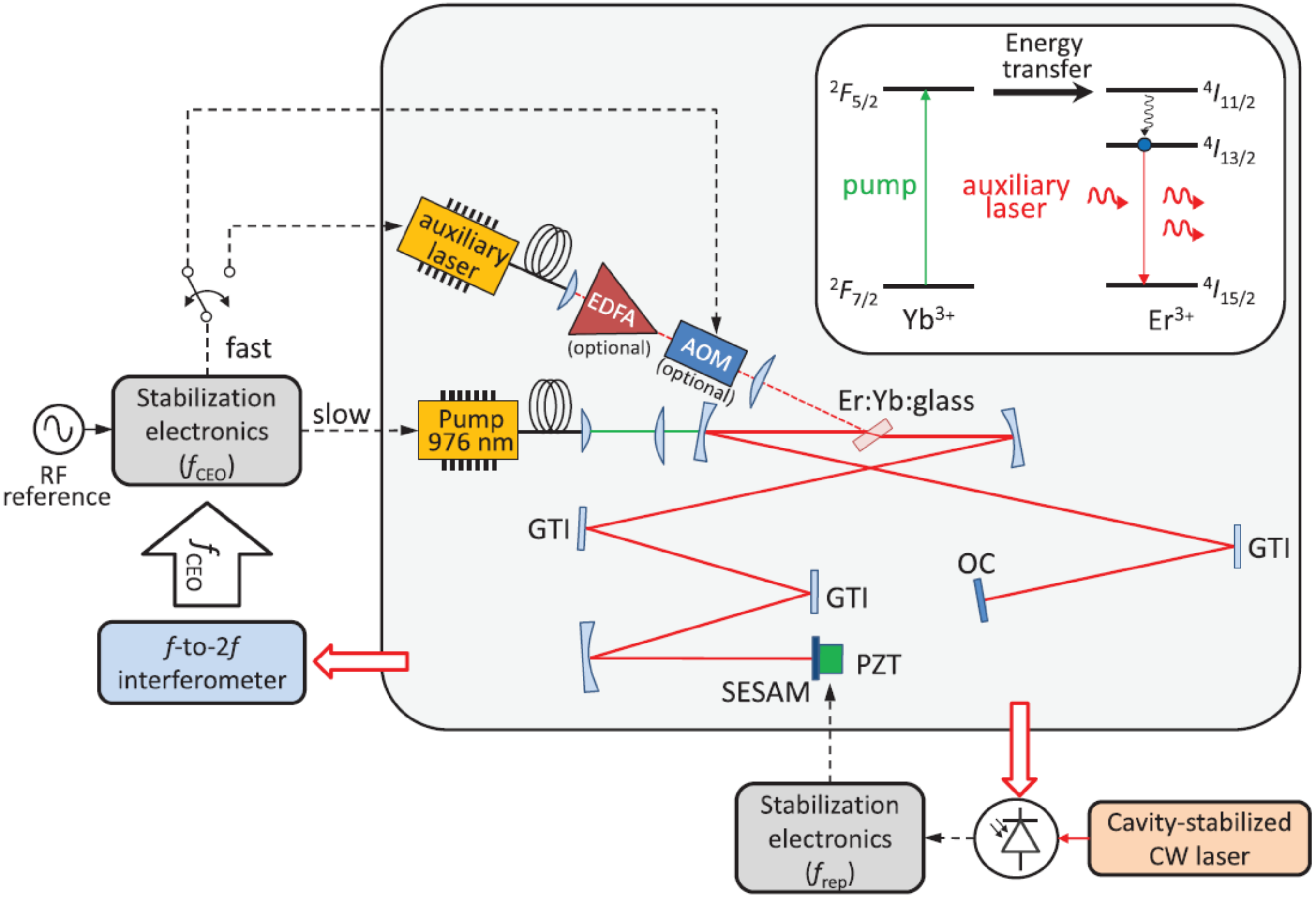
EOM in DPSSL





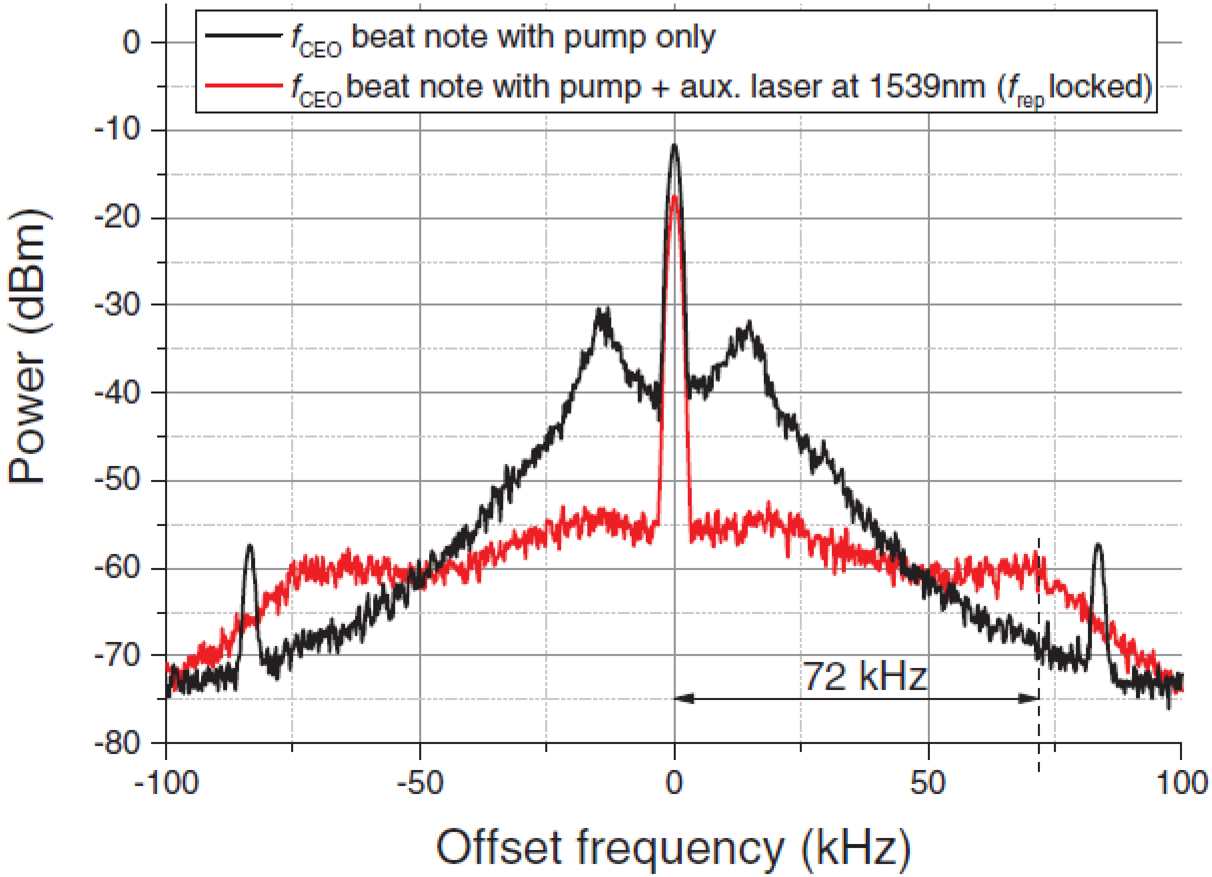
N. Torcheboeuf *et al.*, Opt. Express 25, 2215-2220 (2017)

Power / CEO stabilization via gain control



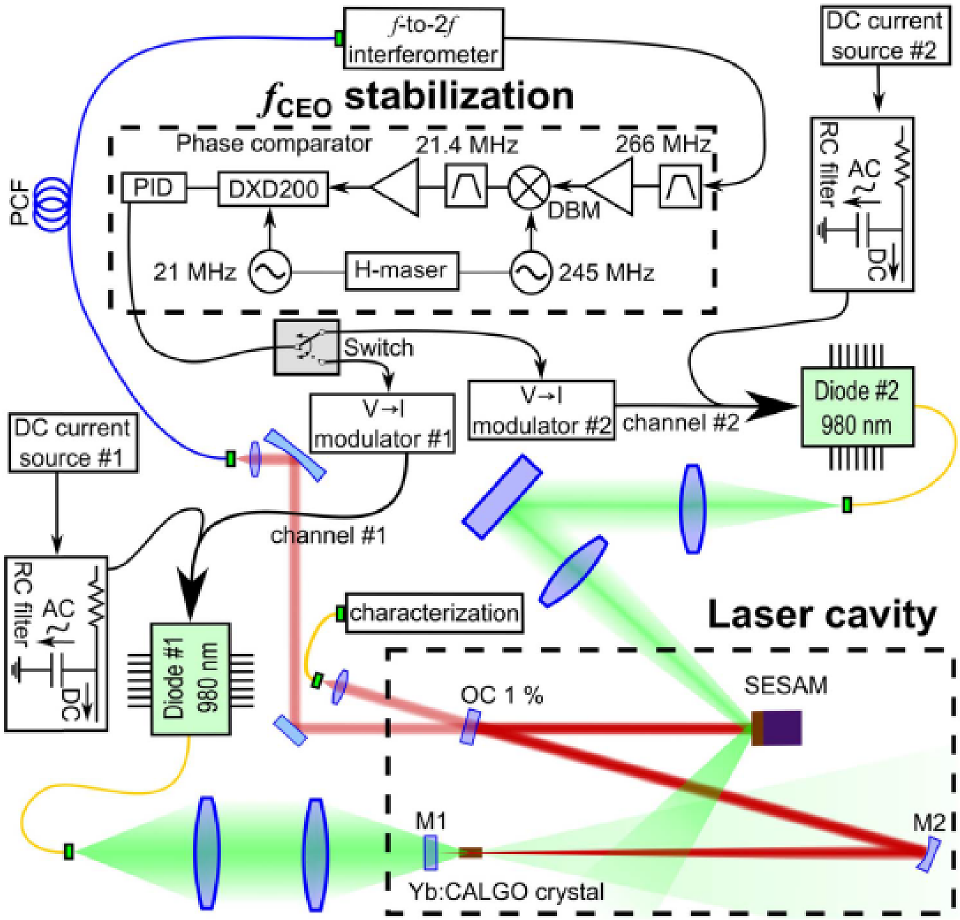
L. Karlen *et al.*, Opt. Letters 41, 376-379 (2016)

Power / CEO stabilization via gain control



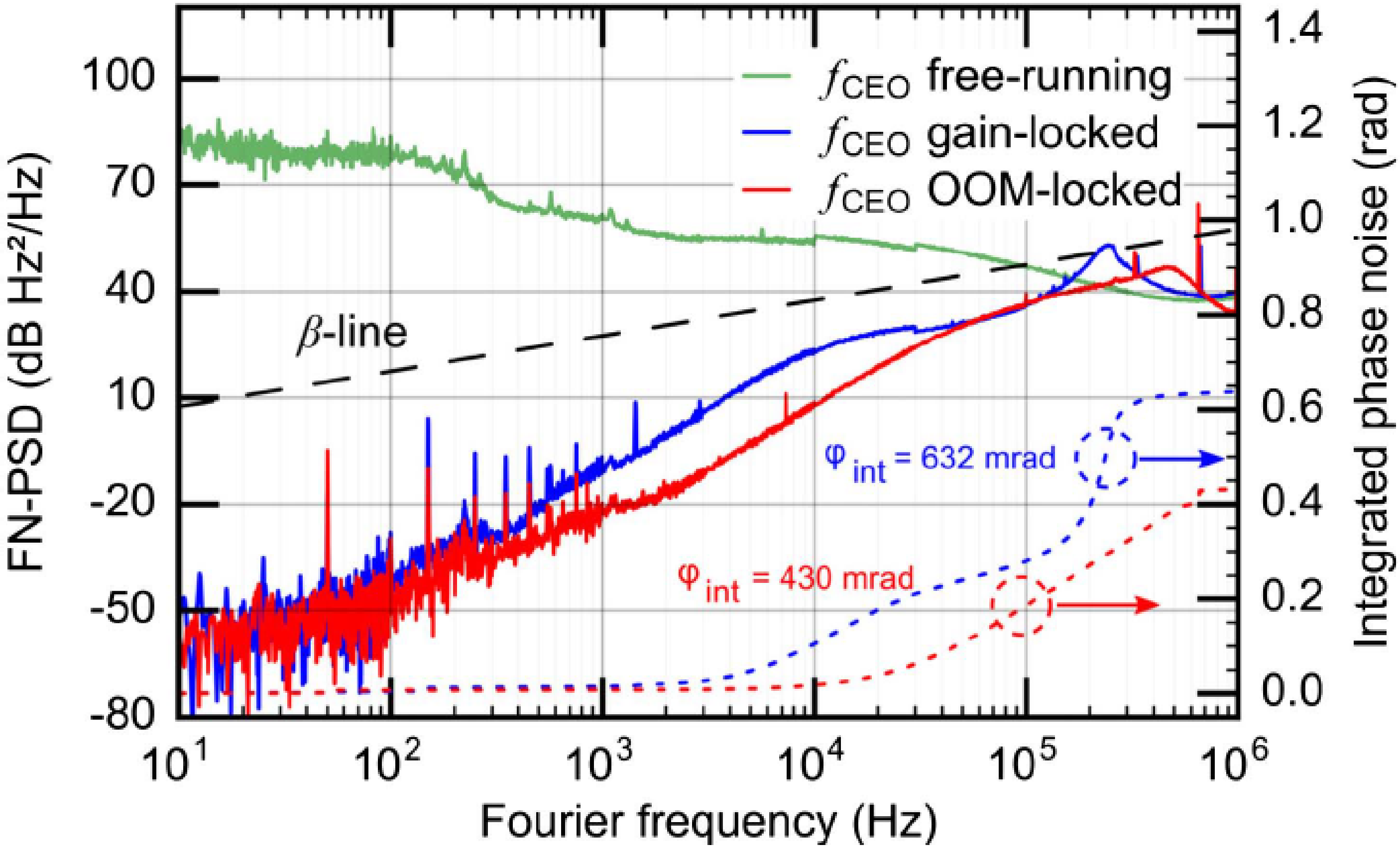
L. Karlen *et al.*, Opt. Letters 41, 376-379 (2016)

Optical actuation on SESAM



S. Hakobyan *et al.*, Opt. Letters 42, 4651-4654 (2017)

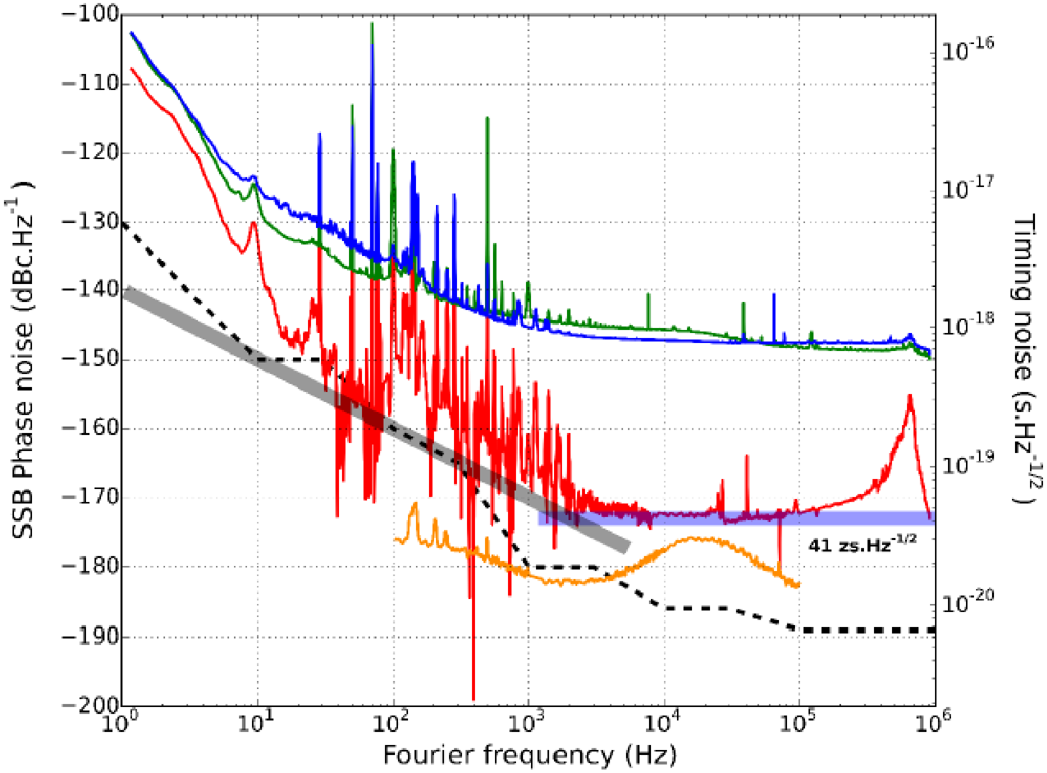
Optical actuation on SESAM



S. Hakobyan *et al.*, Opt. Letters 42, 4651-4654 (2017)

Fiber laser with fast actuators

- EOMs for frep and CEO control allow MHz range locking bandwidths
- Efficient implementation in loss tolerant fiber lasers for tight locking



X. Xie *et al.*, Nat. Phot. 11, 44-47 (2017)

Conclusions and outlook

- fs modelocked lasers are exquisitely good oscillators
- Fundamental and technical noise sources in such lasers are well known and understood
- New laser designs are under development
- Still room to push for improved laser performances via reducing noise sources and optimized stabilization
- Better photonics-based microwave oscillators will be realized

Reference articles

- J. Kim and Y. Song, Adv. In Opt. And Phot. 8 465-540, 2016
- N. R. Newbury and W. C. Swann, JOSA B 24 1756-1771, 2007
- R. Paschotta, Appl. Phys. B, 79 163-173, 2004

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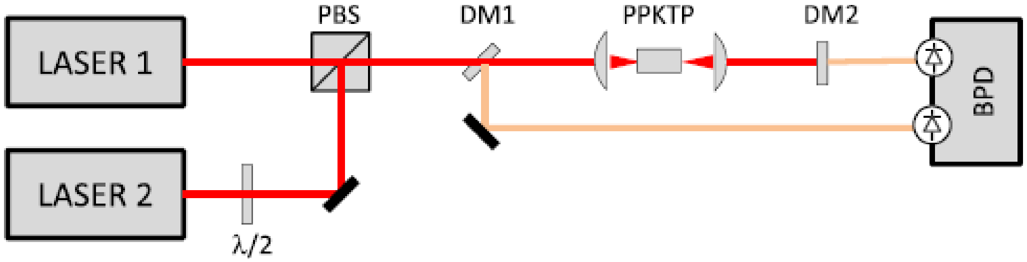
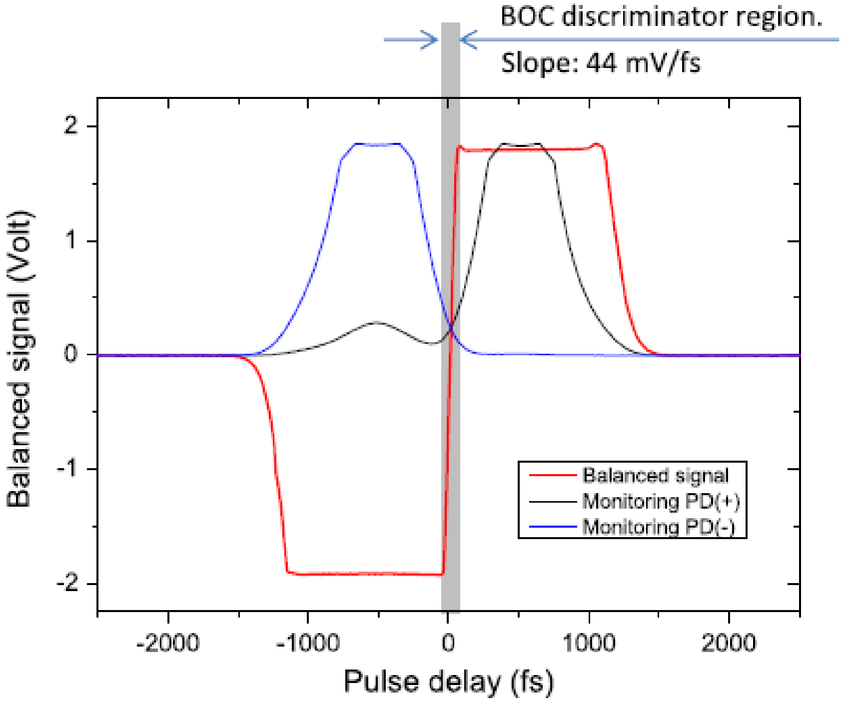
BOC technique



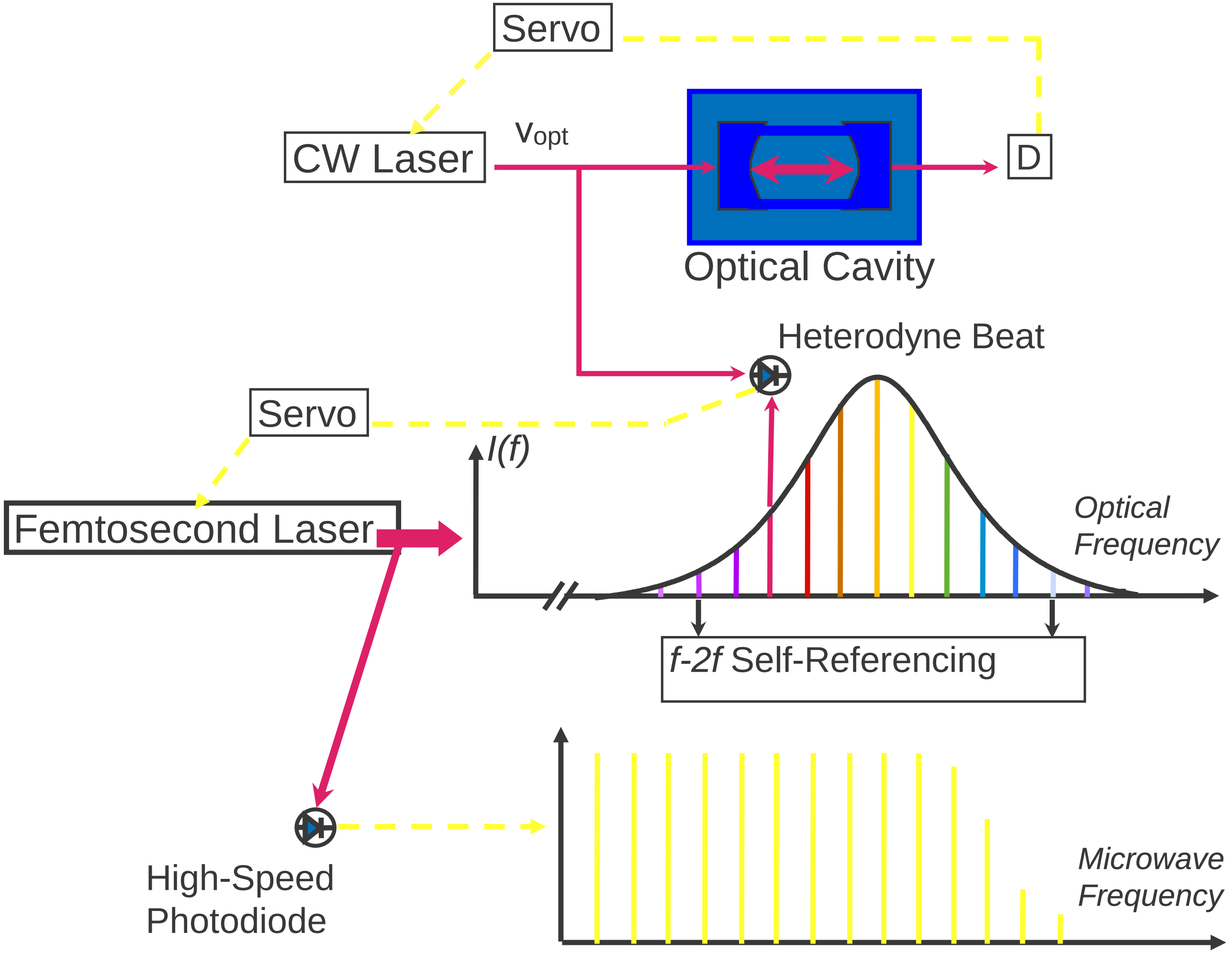


BOC discriminator region.

Slope: 44 mV/fs

E. Portuondo-Campa et al., Opt. Lett. 38, 2650-2653 (2013)

Ultrapure microwave generation



Reference Oscillator

Optical Frequency Comb

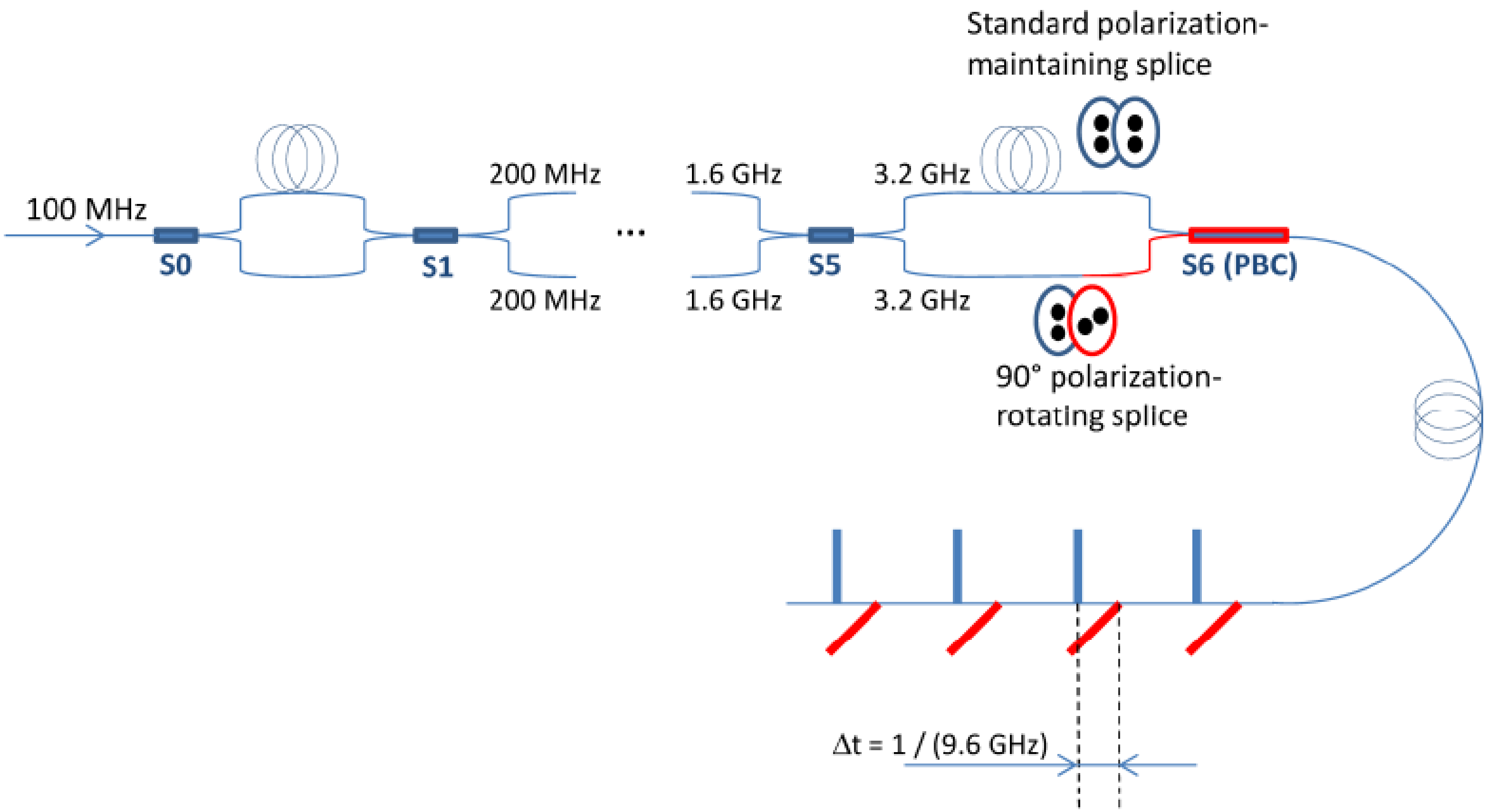
$nf_{rep} + f_o = \nu_{opt}$

Microwave Frequency Comb

$f_{rep} = (\nu_{opt} + f_o)/n$

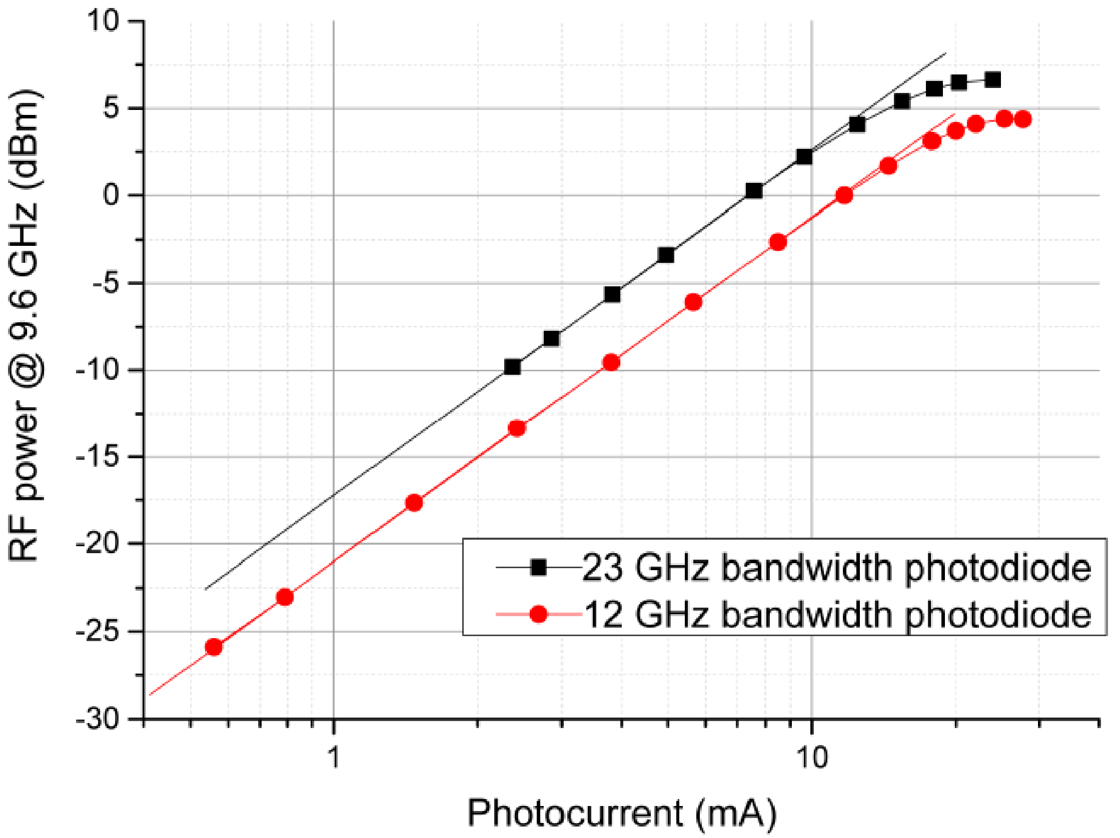
Slide from S. Diddams, NIST

Augmentation du taux de répétition du train d'impulsion



E. Portuondo-Campa *et al.*, Opt. Express 23, 32441-32451 (2015)

Photocourant et sa saturation

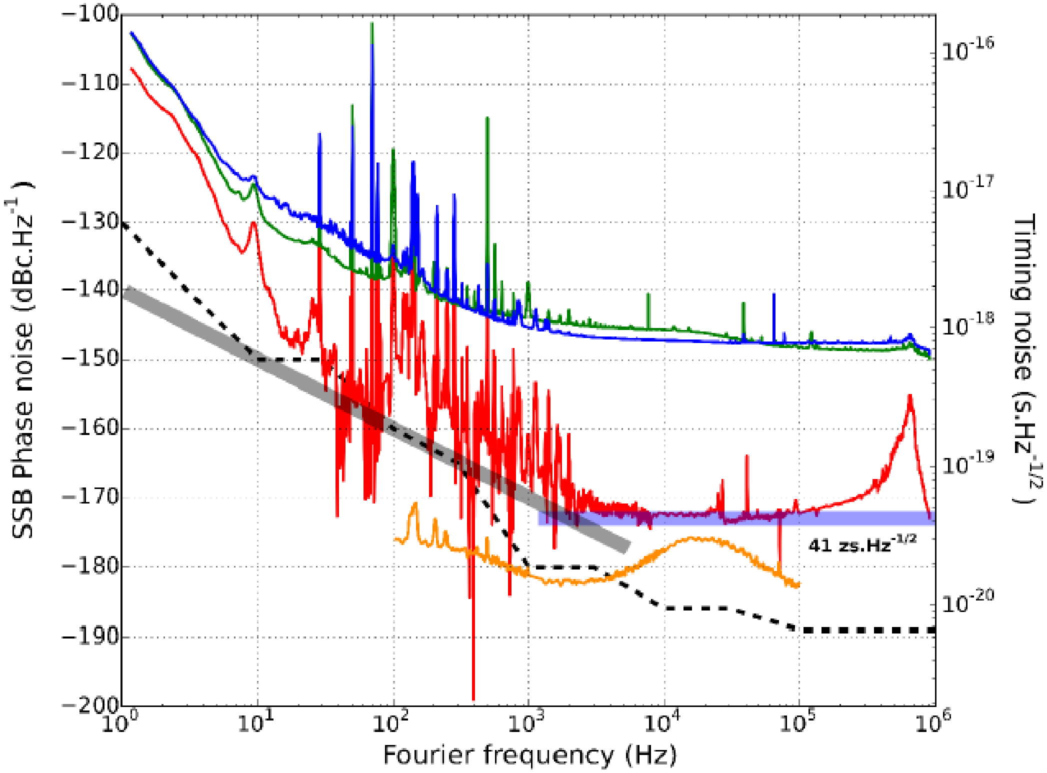


E. Portuondo-Campa *et al.*, Opt. Express 23, 32441-32451 (2015)

Cavité de référence

Fiber laser with fast actuators

- EOMs for frep and CEO control allow MHz range locking bandwidths
- Efficient implementation in loss tolerant fiber lasers for tight locking



X. Xie *et al.*, Nat. Phot. 11, 44-47 (2017)