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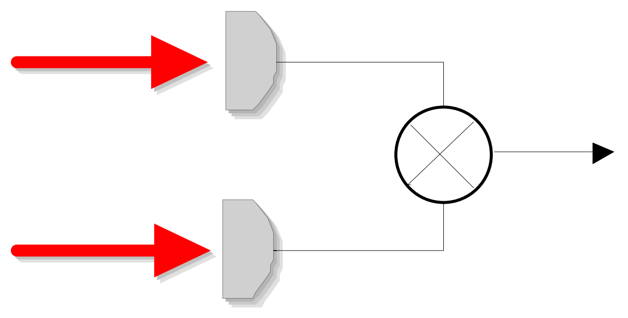


Competence Area:
Fluctuations & Noise

Overview:
Noise in Optics and Electronics

- Why we need to understand noise
- Topics in this area.
  For various topics, the following is given:
  - short description of topic
  - previous activities of R. Paschotta in this field
    (See the website for references on scientific results)
  - examples for possible consulting activities

Note: for more details (with references to publications) on the scientific achievements of R. Paschotta, see
http://www.rp-photonics.com/Science_Paschotta.ppt

Why we Need to Understand Noise

- Noise is often a **limiting factor for the performance** of a device or system.
  Examples: transmission rate of telecommunication system limited by the need to keep the bit error rate low enough; sensitivity of measurements is limited by noise.
- Efficient product development often requires
  - quantification of noise from components
  - calculation of noise effects on system performance
- Noise issues can have an important impact on system cost.
  Example: by choosing the right measurement scheme, which is less sensitive to noise, one might do the job with a less costly laser system.
- Note: incompetent noise specifications can irritate customers!
  If that kind of competence is not available in house, have your staff trained!

Topics in this Area

- Mathematical description of noise
- Origins of noise
- Electronic noise measurements
- Optical noise measurements
- Feedback systems for noise suppression
- Noise modeling

Mathematical Description of Noise

$$G(\tau) = \langle P(t) P(t+\tau) \rangle$$

$$S(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} G(\tau)\, e^{i\omega\tau} \mathrm{d}\tau$$

$$\sigma_P^2 \equiv \left\langle \left(P(t) \right)^2 \right\rangle = G(0) = \int_{-\infty}^{+\infty} S(\omega)\, \mathrm{d}\omega$$

$$\left\langle \left| \phi(T) - \phi(0) \right|^2 \right\rangle = 2\, T / \tau_{\mathrm{coh}}$$

$$\sigma_{\mathrm{cc}}^2 = \frac{1}{f_0^{\,4}} \int_{-\infty}^{+\infty} f^{\,2} S_\phi(f)\, \mathrm{sinc}^2\left(\pi \frac{f}{f_0} \right) \mathrm{d}f$$

Mathematical Description of Noise

- Noise of devices or systems needs to be reliably quantified.
  Reason: designs based on properly quantified noise properties save development time and cost by eliminating trial & error.

- This requires correct measurements, but also **correct and helpful specifications**.

- Specification and comparison of noise properties is not trivial due to

  - manifold types of quantities
    (power spectral densities, correlation functions, probability distributions, etc.)

  - mathematical difficulties
    (related to divergent quantities, required approximations, statistics, etc.)

  - inconsistent notations in the literature
    (different sign conventions, one- or two-sided power spectral densities, f or ω variables, 2π issues, etc.)

  Only a real expert can do reliable and efficient work in this field.

Mathematical Description of Noise

Examples for previous activities of R. Paschotta:

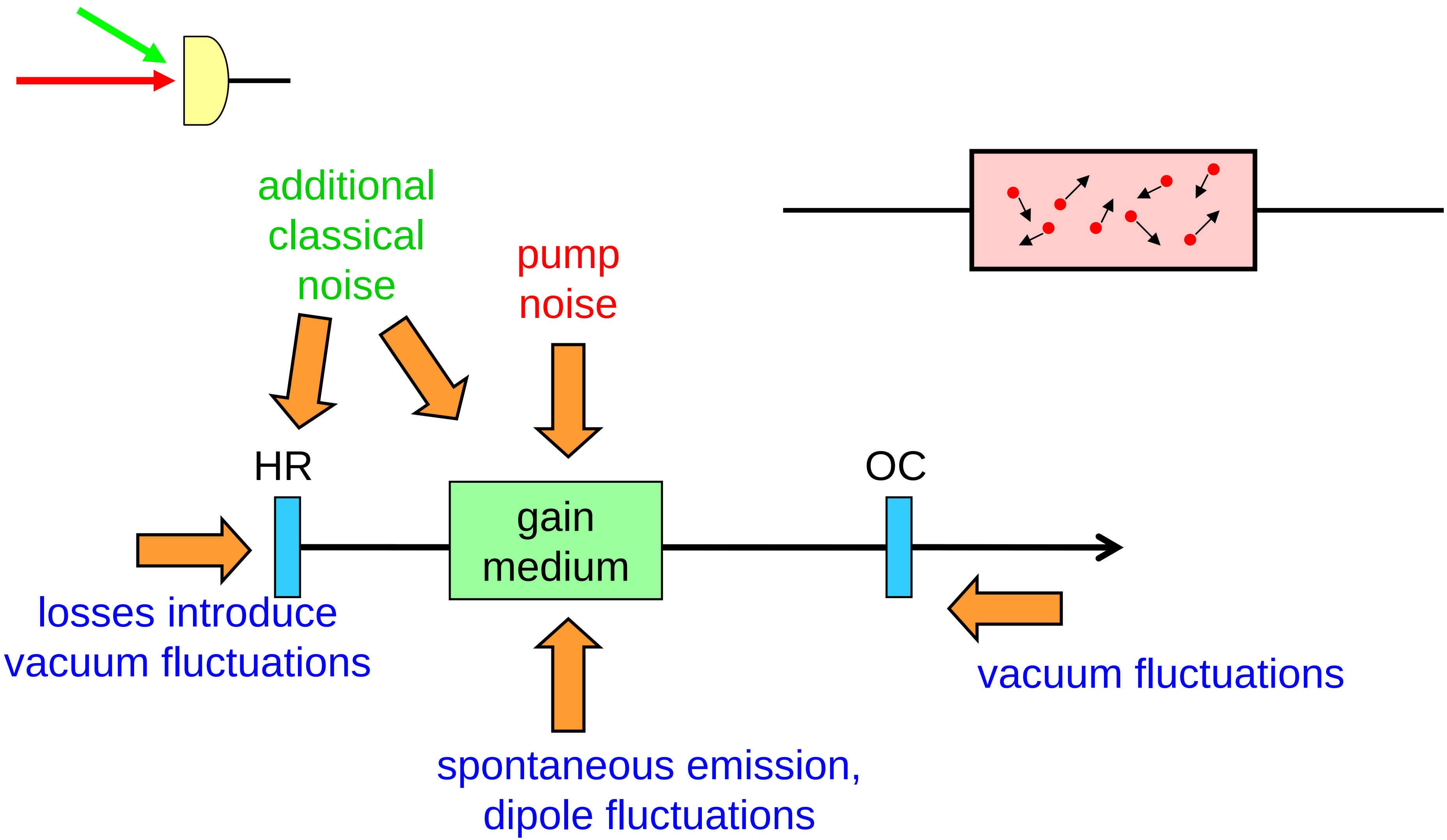
- Extensive calculations on quantum noise and thermal fluctuations in optics and electronics
- Group-internal teaching on noise specifications

Mathematical Description of Noise

Examples for possible consulting activities:

- Checking noise specifications of a product for completeness and soundness, so as to convince your customers.
  Investing just half a day of consulting can help to secure sales.
- Comparing noise specs of your product to theoretical expectations.
  Otherwise you won't know whether there is room for further improvement.
- Checking whether the noise specs of a product will be sufficient for your application, or compare noise specs of different products, or calculate limits to the expected performance.
  Don't loose a lot of money by trying things which can't work, or by buying the wrong product.
- Training your personnel in such areas.
  Is there a more cost-efficient way to obtain solid know-how?

Origins of Noise



Origins of Noise

- **Thermal fluctuations:** often an important source of noise in electronic circuits, e.g. in photodiode preamplifiers
- **Other electronic noise**, e.g. flicker noise: various sources; may critically depend on parts used
- **Quantum noise:** often important in optical devices, e.g. shot noise in photodetection or intensity and phase noise in lasers
- **Mechanical noise:** e.g. in the form of vibrations which can couple to optical or electronic parameters

Origins of Noise

Examples for previous activities of R. Paschotta:

- Comparison of noise influences in highly nonlinear pulse propagation in photonic crystal fibers
- Comprehensive analysis of various noise influences on the timing jitter and the optical phase noise of mode-locked lasers, using a combination of new analytical calculations and numerical techniques

Origins of Noise

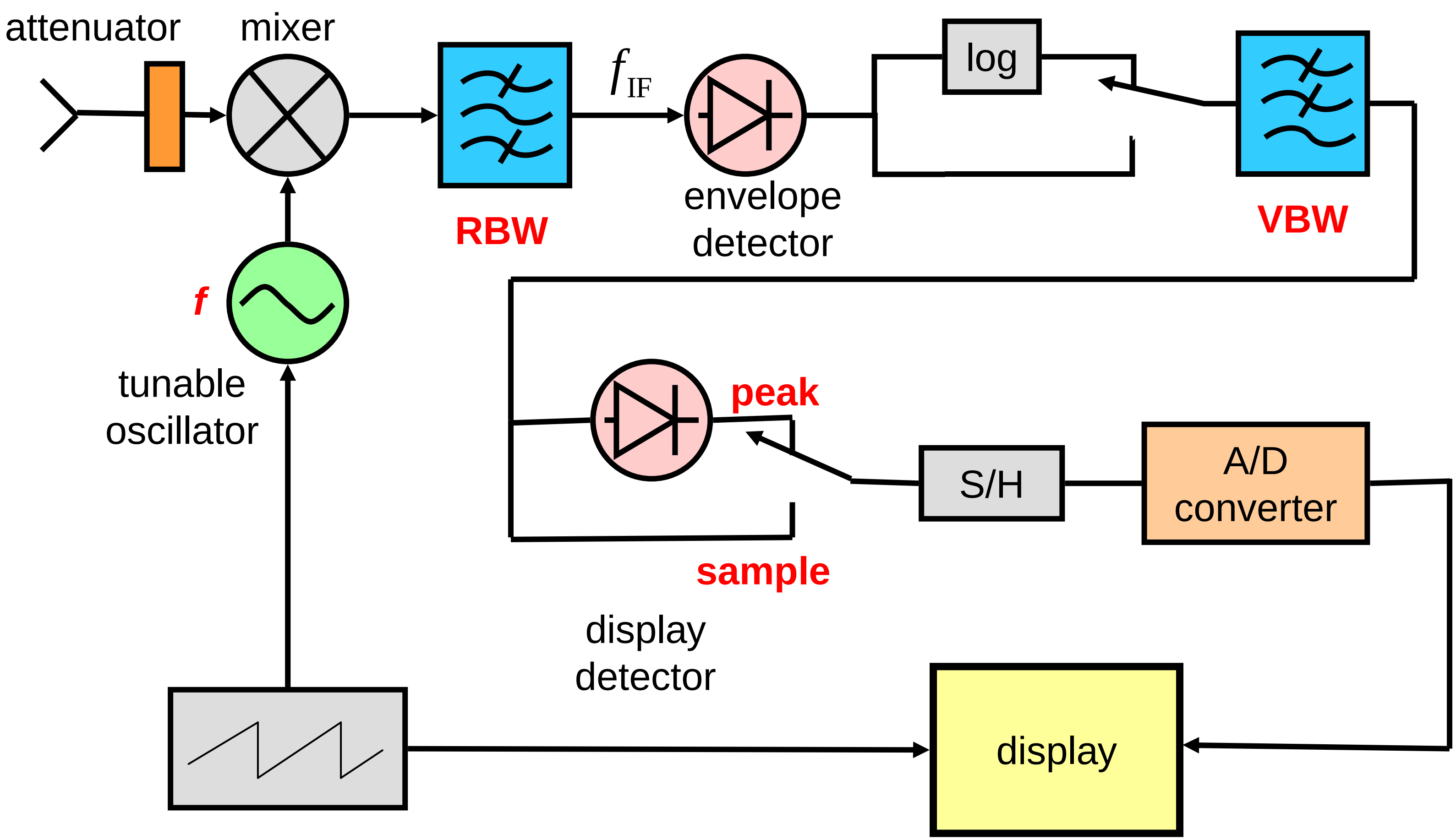
Examples for possible consulting activities:

- Calculate the expected impact of different noise sources on the performance of your product.
  Or would you prefer guess work to guide your development?

- Identify the dominating effect
  to avoid working on the wrong aspect

- Identify the key factors for optimization and quantify the remaining potential
  so that your decisions will be well founded

Electronic Noise Measurements



Electronic Noise Measurements

- Noise in electrical signals is often measured with **RF spectrum analyzers**.
- Such measurements are prone to an **intimidating ensemble of possible errors**:
  - confusion between 3-dB bandwidth and effective noise bandwidth
  - statistical effects from averaging logarithmic (dBm) values
  - wrong detector mode: peak detector overestimates noise, particularly when combined with wrong video averaging
  - saturation of mixer or logarithmic amplifier by signals outside the displayed range
  - influence of phase noise from local oscillator
- Correct noise measurements with an RF spectrum analyzer require a decent understanding of how such a device works.

Electronic Noise Measurements

Examples for previous activities of R. Paschotta:

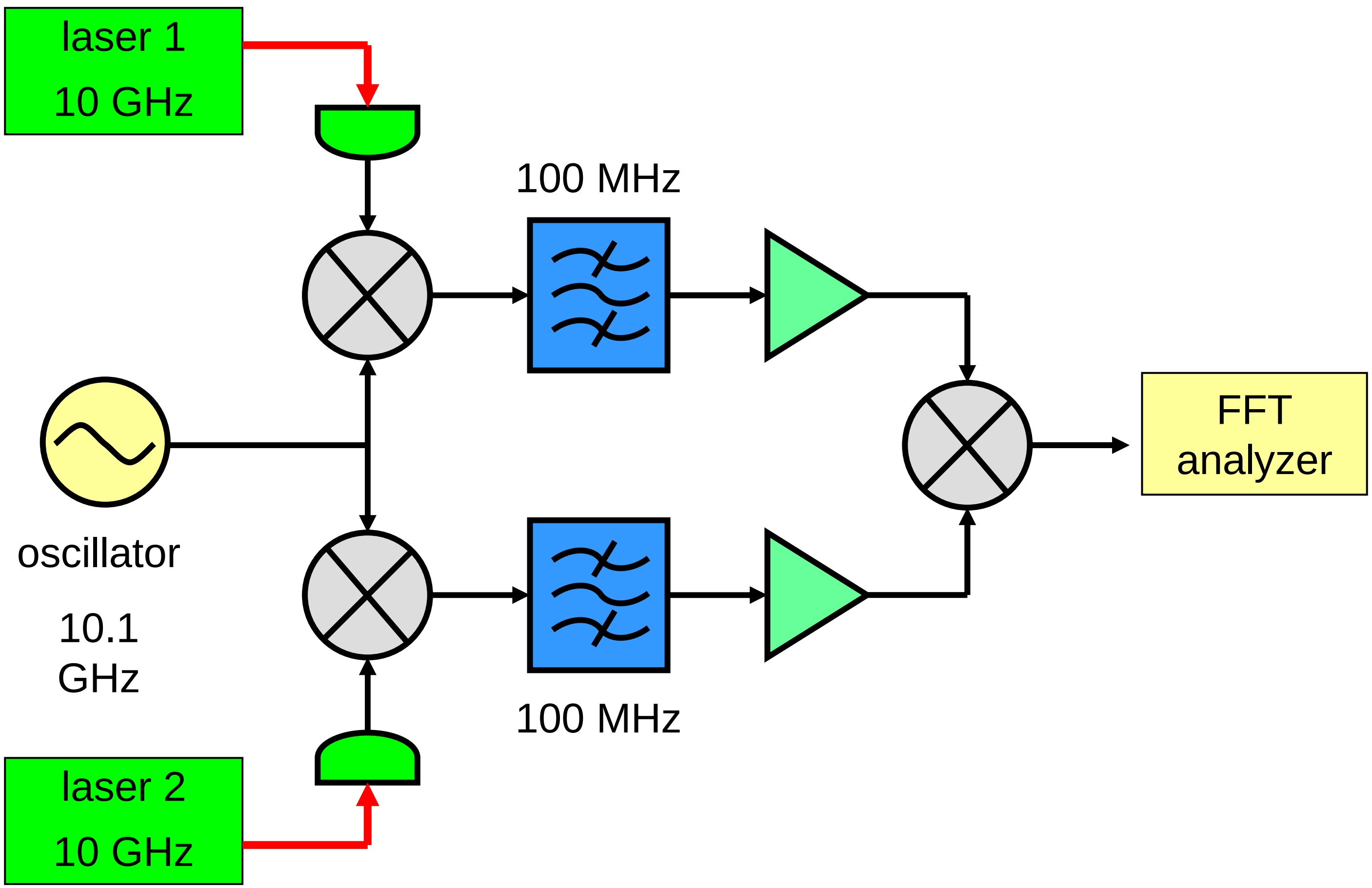
- Acquired a deep understanding of electronic spectrum analyzers
- Optimization of photodetector circuits for noise measurements below the shot noise limit
  ($\rightarrow$ experiments with nonclassical states of light)
- Development of new measurement schemes for low levels of phase noise
- Detailed lecturing

Electronic Noise Measurements

Examples for possible consulting activities:

- Comparison of different technical approaches for noise measurements
  ideally before you heavily invest into some scheme
- Development of a measurement setup, or checking an existing setup and proposing improvements
  in a process during which your engineers can learn a lot
- Checking the data processing to ensure validity of the obtained data

Optical Noise Measurements



Optical Noise Measurements

- Intensity noise: measurements e.g. with photodiodes or photomultiplier tubes
- Phase noise: beating with reference laser; heterodyne measurement with unbalanced Mach-Zehnder interferometer
- Timing jitter of mode-locked lasers: various measurement schemes exist – high demands for low jitter levels!

Optical Noise Measurements

Examples for previous activities of R. Paschotta:

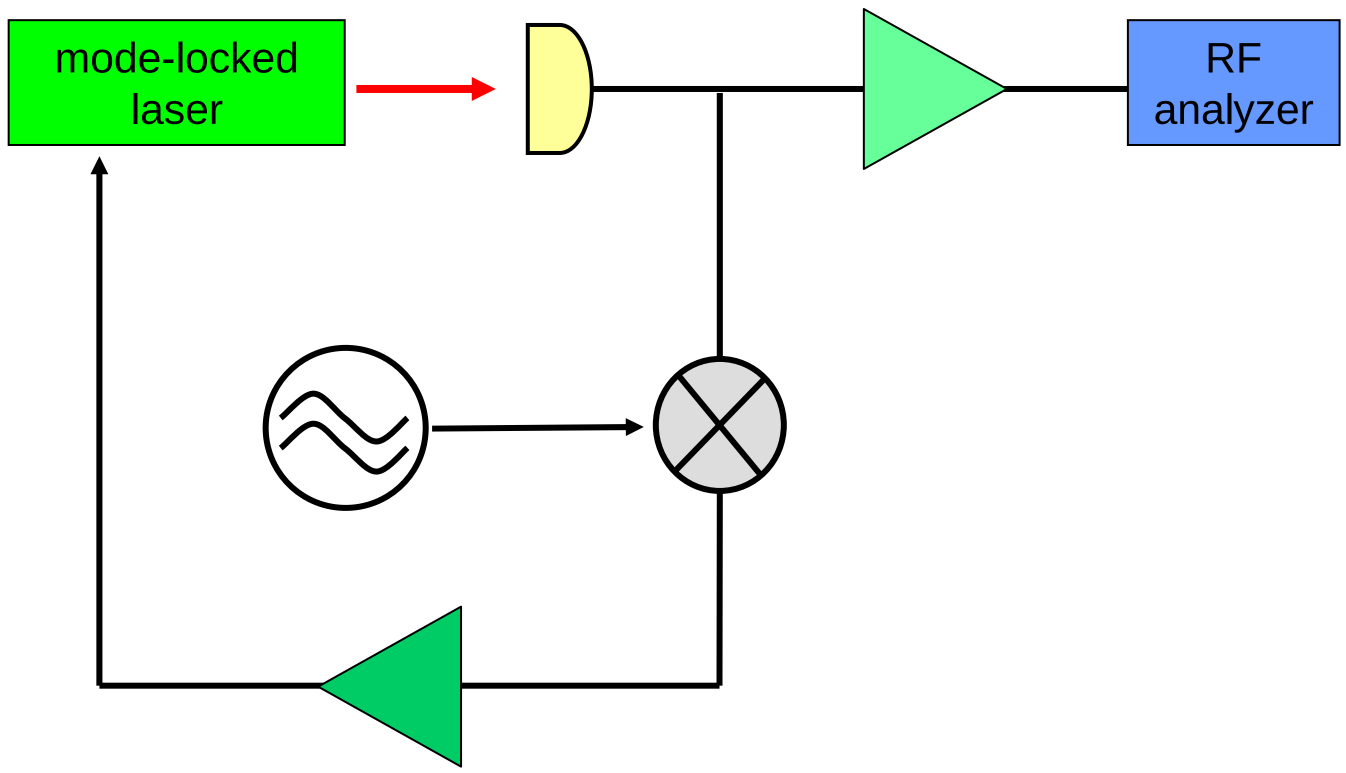
- Detection of nonclassical ("squeezed") states of light below the shot noise limit
- Development of a novel measurement technique, which is very sensitive, very versatile (can be applied to free-running or timing-stabilized mode-locked lasers), and does not require an ultrastable electronic reference oscillator

Optical Noise Measurements

Examples for possible consulting activities:

- Compare different measurement techniques
- Help to set up measurements of relative intensity noise, phase noise, or timing jitter
- Identify limiting factors of existing measurement setups and propose possible improvements

Feedback Systems for Noise Suppression



Feedback Systems for Noise Suppression

- Noise can often be suppressed with automatic feedback systems. Examples:
  - Stabilization of a laser output power
  - Stabilization of the gain or average output power in telecom amplifiers
  - Phase locking the pulses of a mode-locked laser to an electronic reference
- Effective stabilization and suppression of oscillations requires well-designed feedback loop
- Limits for stabilization arise from dead times, electronic noise, quantum effects, etc.

Feedback Systems for Noise Suppression

Examples for previous activities of R. Paschotta:

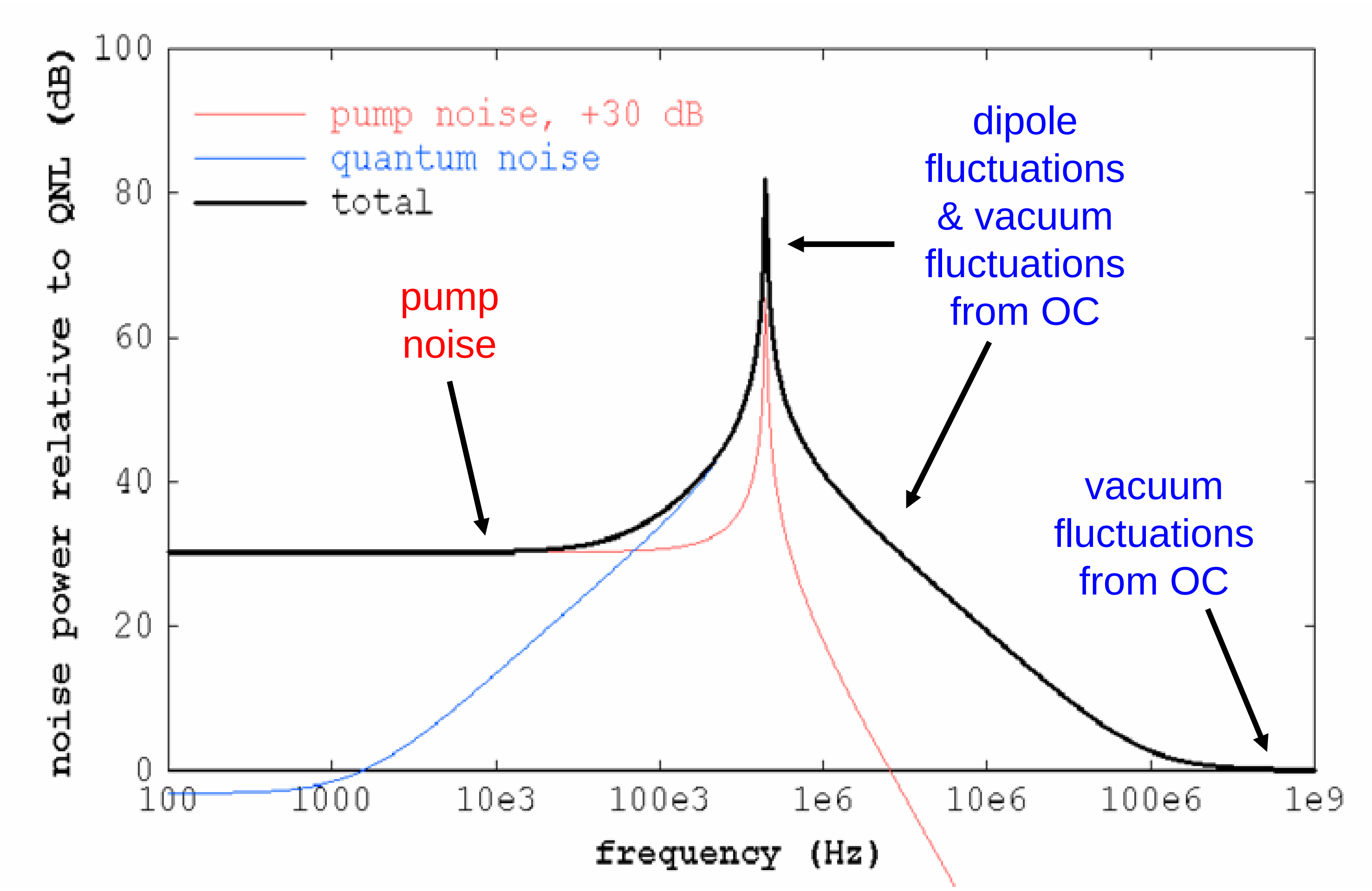
- Designed and operated various electronic feedback systems
- Developed advanced schemes for timing stabilization of mode-locked lasers

Feedback Systems for Noise Suppression

Examples for possible consulting activities:

- Design or check an electronic feedback system for the stabilization of an optical power
- Help to optimize the performance, considering control elements, optimized frequency response of feedback electronics, possible feed-forward schemes, etc.

Noise Modeling



Noise Modeling

- Models can greatly help to
  - identify limiting factors
  - optimize the design before trying in the lab
  - verify by comparison with measurements whether the expectable performance is reached
- Analytical and/or numerical techniques are required, depending on the circumstances
- Noise modeling requires detailed know-how on mathematical issues, numerical techniques, physical effects, and technical possibilities, and extensive general experience of working with models.
- Note: Setting up a model is one thing – producing results is another one!

Noise Modeling

Examples for previous activities of R. Paschotta:

- Analytical calculation of quantum noise properties of lasers, frequency doublers, parametric oscillators, etc.
- Numerical simulation of noise in highly nonlinear pulse propagation in photonic crystal fibers, and studies of its effects on pulse compression
- Modeling of timing noise and other noise properties of mode-locked lasers, based on quantum noise and classical noise inputs

Note: R. Paschotta has developed extremely powerful and versatile simulation software, allowing to get quick and reliable results in graphical or text form.

Noise Modeling

Examples for possible consulting activities:

- Give advice on what kind of model will be feasible, useful and efficient
- Set up a model and use it to answer concrete questions,
  e.g. on
  - critical parameters
  - possibilities for optimization
  - effects of noise in components and systems
    (e.g. timing jitter, carrier-envelope offset noise, impact in metrology,
    e.g. in interferometers)