How to Make a Transparent Laser
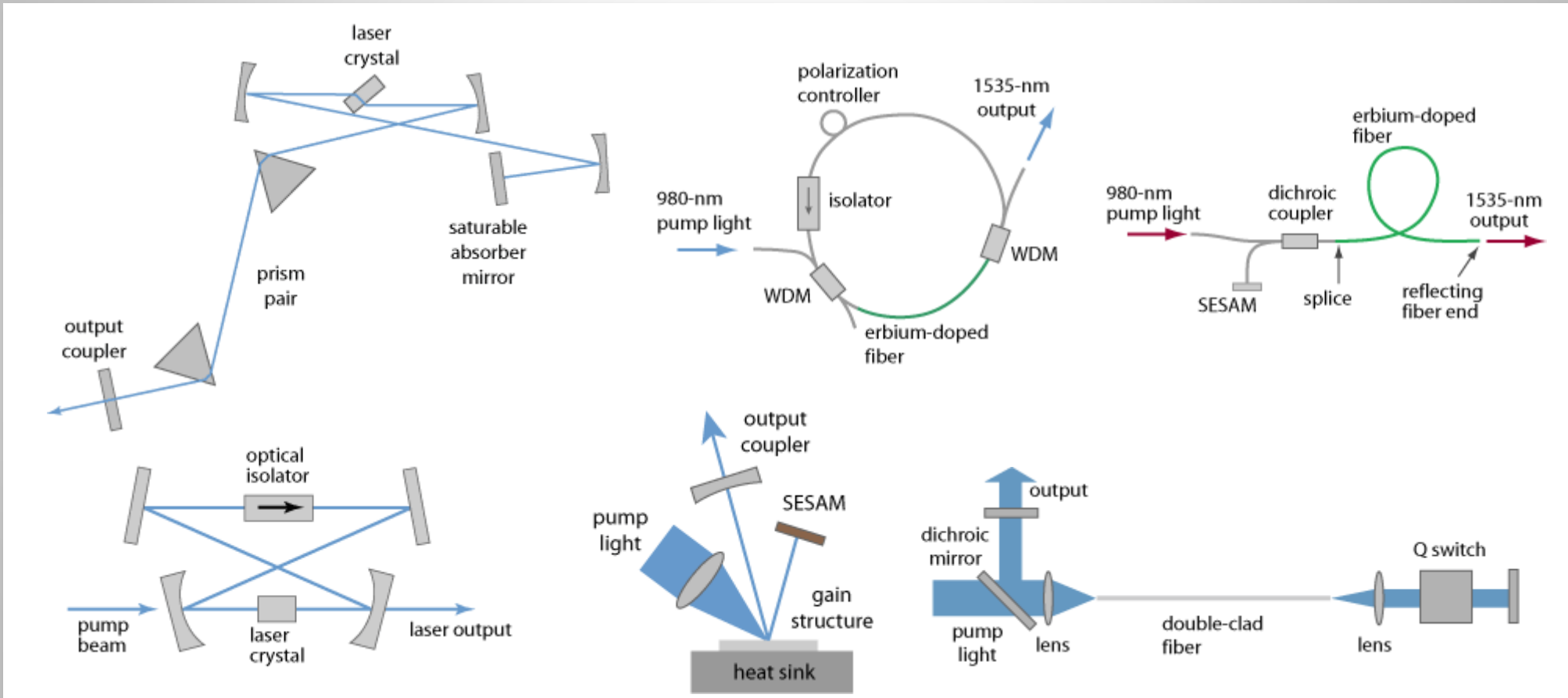
Thoughts on a common challenge in laser development and on modeling as a powerful solution

thoughts and insights from
Dr. Rüdiger Paschotta, RP Photonics Consulting GmbH
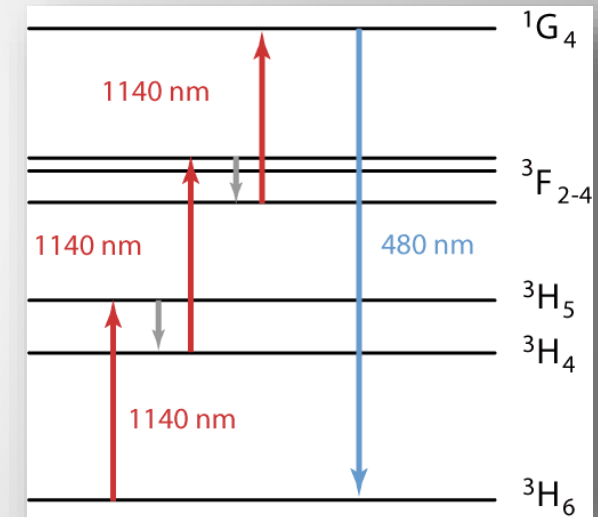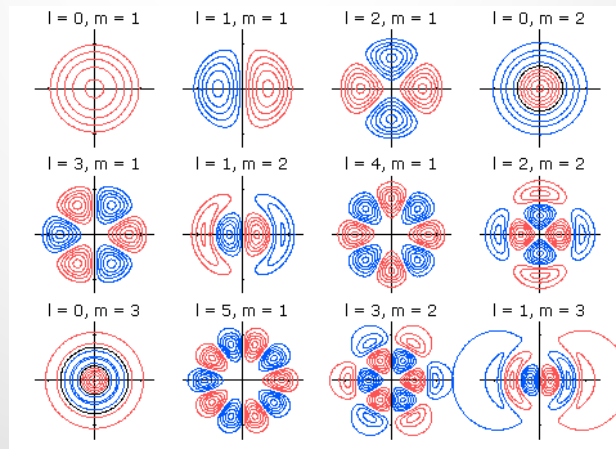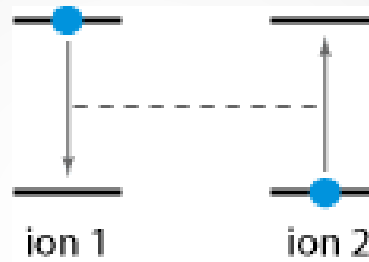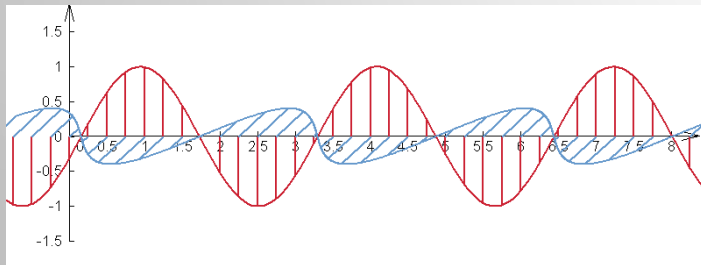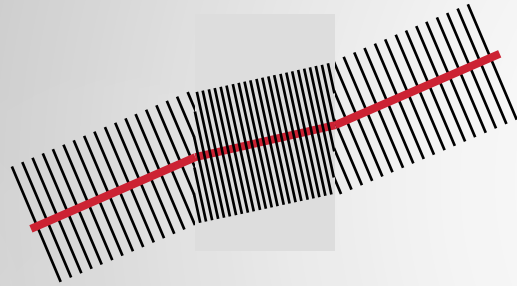www.rp-photonics.com/software.html

The Design of a Laser Product

▶ The **design** defines what components are used, where they are positioned, etc.

The Basis of a Design

▶ Such a design is always based on more or less detailed **mental conceptions about internal phenomena** like pumping of laser-active ions, stimulated emission, saturation effects, propagation modes, etc.

What Can You Learn from Experimental Tests?

▶ Ultimately, a design must be proven to work in experimental tests: build the laser, operate it, and check what comes out.

▶ Experimental tests, however, can often reveal only to which extent the achieved **performance** is as desired – but **essential questions may stay unanswered**:

  ▶ Why is the performance so poor?

  ▶ What goes on inside the laser device?

  ▶ What is the cause of some observed strange behavior?

▶ A basic problem of lasers: **you cannot look into** a laser crystal, an active optical fiber, a frequency doubler or whatever component in order to **see what happens inside**. You cannot even put your powermeter or beam profiler into an air space in a laser resonator.

The Laser as a Black Box

▶ Your experimental laser setup behaves like a kind of **black box**: you can analyze what comes out, but not what happens inside.

laser   diagnostics

▶ This problem is typical for many photonic devices, but it is different for electronic circuit boards, for example: there, you may easily probe voltages at various locations.
The essential differences: light fields, other than electrical signals in wires, can have complicated spatial structures, and they are strongly affected by the presence of diagnostic means.

▶ The trouble: **how to fix problems** if you don't understand their causes and effects of possible design changes? **With trial & error??**

RP Photonics

The Transparent Laser – a Dream?

▶ Imagine for a moment that you would build a laser
from **transparent components**,
where you could simply **look inside and see what happens**:

  ▶ What are the optical intensities at any location (with micrometer
    resolution) and any time (with nanosecond or femtosecond resolution)
    inside your laser crystal, fiber or frequency doubler?

  ▶ How does the beam quality of the laser radiation at any location
    evolve during the pulse build-up?

  ▶ How does the excitation of laser-active ions evolve?

▶ Sure, that would be marvelous – finally, you could find out what
exactly happens inside and how to fix any problems – …
… but isn't that just a dream? (Where to buy such components??)

▶ Good news: you can indeed make whole lasers (and more) with all
transparent components – see the next page!

Making a Transparent Laser

- The trick: create a **computer model of your laser**, which

    - contains a simplified description of the device
      (e.g. length of active fiber, doping concentration in the fiber core,
      transition cross sections of the active ions, seed pulse properties, etc.)

    - simulates all essentially processes

    - calculates the observable performance from that

    - and nicely presents all results – observable quantities as well as any
      internal details – e.g., as numerical values or in graphical diagrams.

- What you need for such modeling is:

    - an ordinary PC

    - suitable software

    - data of the components

    - a decent know-how and/or competent technical support

RP Photonics

Example: Fiber Laser Design

▶ A powerful **fiber optics software** (e.g., RP Fiber Power) can, e.g.,

   ▶ simulate pump absorption and amplification in an active fiber

   ▶ do numerical beam propagation, e.g. with bending effects

   ▶ simulate the amplification of ultrashort pulses
   (including chromatic dispersion, nonlinearities, etc.)

▶ Use that to learn how fiber lasers and amplifiers really work,
and how to develop optimized designs.
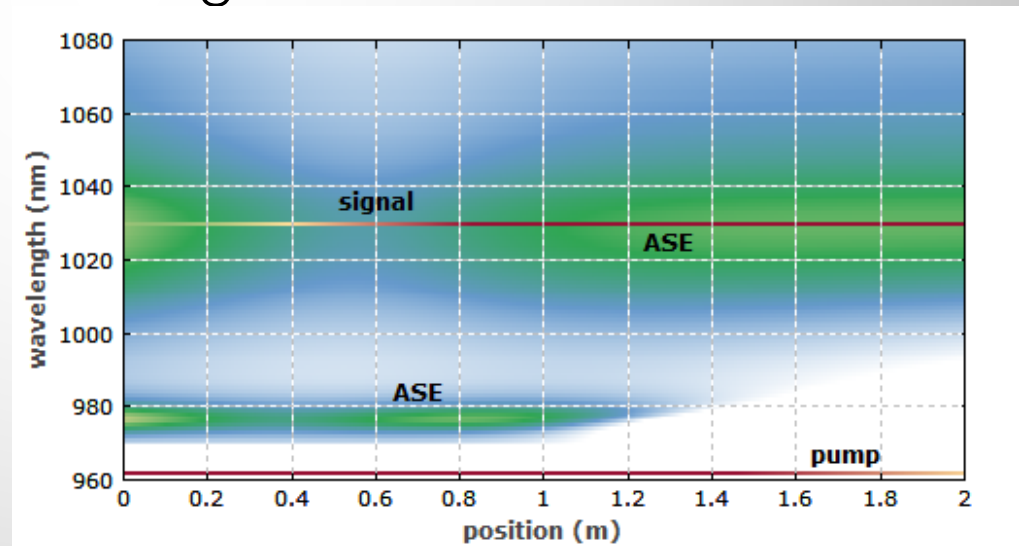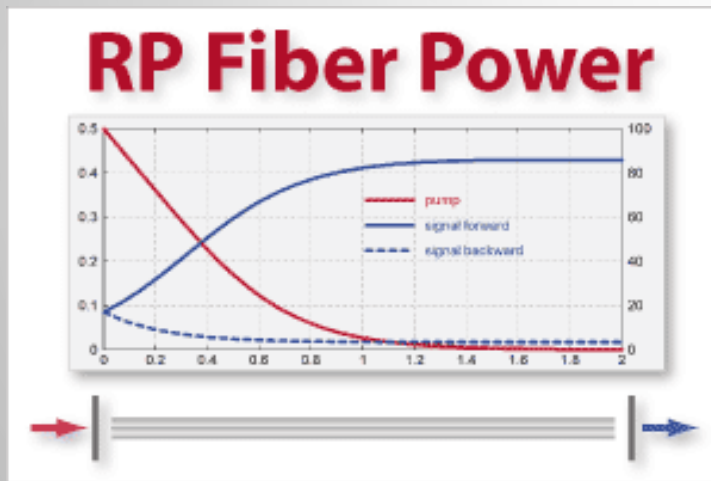
Example: Laser Resonator Design

▶ A powerful **resonator design software** (e.g., RP Resonator) can calculate any properties of laser resonator modes:

  ▶ mode sizes e.g. in a laser crystal, in a frequency doubler or on mirrors

  ▶ their sensitivity to thermal lensing effects and to misalignment

▶ Use that to learn how laser resonators really work,
  and how to develop optimized designs for more power, better
  beam quality, lower alignment sensitivity, …
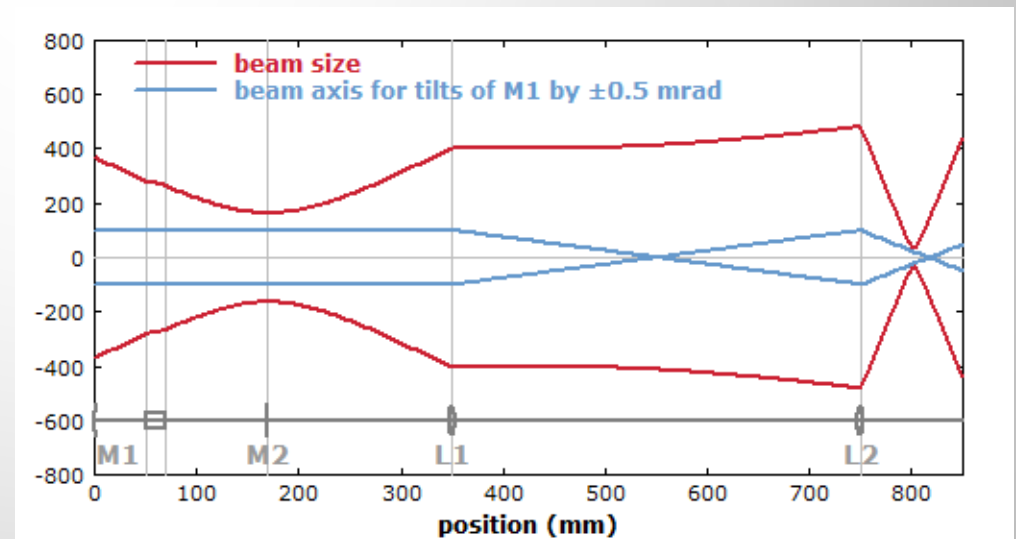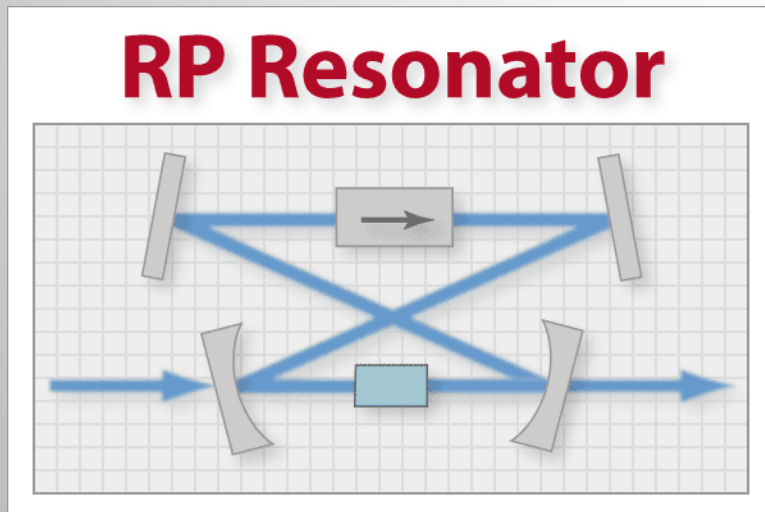
Example: Mode-locked Lasers

▶ A pulse **propagation software** (e.g., RP ProPulse) can simulate how ultrashort light pulses evolve in mode-locked lasers, amplifier systems, parametric oscillators, etc.

▶ Use that e.g. to learn which operation regimes are stable, and on which parameters the stability and performance depends.

RP ProPulse

RP ProPulse

No steps: 200   (200 roundtrips, 200 ns)   ☑ Show statistics   Save, t   Save, f   Load
Position: start position   Movie   ☑ Show grid lines   ☑ Show steps   Save   Clip   Store

Time domain   ☐ centered   Display: phase (continuous)   ☑ Auto scale

Energy: 9.63 pJ
Average power: 9.63 mW
Peak power: 185 W
Duration: 45 fs
Mean pos.:   80.7 fs
Peak at: 85.6 fs

phase (continuous) (rad)   time (fs)

Frequency domain   ☑ wavelength axes   ☐ modes   Display: energy   ☑ Auto scale

Peak wavelength: 1060 nm
Mean wavelength: 1066.23 nm
FWHM bandwidth: 5.24 THz, 19.7 nm
TBP (from FWHM): 0.236
TBP_v: 2.06

energy (fJ/nm)   wavelength (nm)

RP PHOTONICS

Working with Laser Models

▶ It is obvious that a tool telling you what exactly goes on in your lasers (or amplifiers, other optical setups, etc.) is extremely useful: **it ends your blind flight** and allows you to **understand and fix problems** in an efficient manner.

▶ In the following, you learn more in detail how to utilize a model

  ▶ for developing a good prototype design

  ▶ for understanding your real laser, even if discrepancies occur

  ▶ for working out your final product design

  ▶ for resolving problems with unexpected behavior

Developing a Prototype Design

▶ Before ordering any real components (which costs a lot of money and time), work out a **prototype design** on your computer.

▶ Describe your conceived design in the software and get its performance simulated.

▶ Thoroughly check the results:

   ▶ Are the performance goals met?

   ▶ Are all parameters in safe regions and not excessively sensitive?

   ▶ If unexpected things happen:
   look into the laser to see what happens inside.
   If you encounter any problem, you will understand it for sure!
   (In difficult cases, use the technical support.)

▶ Revise your prototype design as needed, until
you arrive at a well working prototype design.

▶ All this can often be done *within a single working day*.

Testing a Design in the Lab

▶ Now you can order real components; you now know what you need!

▶ Build your prototype in the lab. Test its performance.

▶ If it works as expected: great, you have done a big step forward! Also, you know that further tweaking makes no sense.

▶ If the performance is not as expected, or unexpected behavior is observed:

    ▶ Check whether the real laser matches your planned design.
      For example, any laser mirrors mixed up (e.g., wrong curvature)?

    ▶ Possibly check isolated components: do they meet their specs?
      (For example, pump absorption in laser crystal as expected?)

    ▶ If no discrepancy is found: was the model possibly oversimplified?
      For example, forgot to include ASE in an amplifier with high gain?
      If you worked well before (having competent support), this is unlikely.

RP PHOTONICS

What if a Discrepancy Occurs?

- ▶ Note: a disagreement between experiment and simulation does not necessarily mean that your model failed:

    - ▶ An error in the model (e.g., overlooked effect, wrong data, or just a stupid mistake) might have caused a discrepancy.

    - ▶ Often, however, the optical components are not as you expected:

        - ▶ The vendor may have violated the specs.

        - ▶ A component may have been damaged or made dirty.

        - ▶ You may have mixed up components.

    - ▶ In other cases, the setup may not be properly aligned, or something is wrong with electronic drivers.

- ▶ Learning about a discrepancy as soon as possible is useful!

RP PHOTONICS

You Could Try to Design your ProtoType Without a Model …

… but would be likely to encounter various problems – for example:

▶ You may find in the experiments that some components need to be exchanged (e.g., need more pump power): have to order new components, spending more money and waiting for delivery again.

▶ You may damage components, e.g. if excessive optical intensities occur. Have to order replacements, modify the design, …

▶ If some problem occurs – for example, unstable pulse generation in a mode-locked laser –, it may be very difficult to find the cause and fix it. There can be many different possible causes, and each one may require different countermeasures.

Seemingly never-ending problems are indeed not uncommon …

RP PHOTONICS

Testing Design Changes

▶ **Any design change can be quickly and reliably tested with a computer model:**

  ▶ Do not need to order new components and test them in the lab.
    Order only later on what can really be expected to work!

  ▶ If your design doesn't work as expected, you will quickly find out why and how to correct your decisions.
    (Failed experiments are far more difficult to correctly explain!)

  ▶ A change of performance observed in a model cannot result from misalignment, dirt, component damage, changed temperature, etc. You can be sure that nothing in the model changed if you did not change it.
    → You get conclusive results!

  ▶ If it hasn't worked, you easily get back – **no tedious rebuilding**!

▶ **Avoid wasting time and money**;
  work with understanding instead of doing a blind flight.

Towards a Final Product Design

▶ Even if your prototype works well, some further revisions may be required:

  ▶ Your boss or your customer wants even more performance …

  ▶ Some tolerances (e.g. for misalignment) may turn out to be too strict.

  ▶ You may want to work with fewer or cheaper components.

▶ Again, the model will greatly help you in refining your design: understand the effect of each design change without doing expensive, time-consuming and possibly misleading experiments.

RP PHOTONICS

Troubleshooting

▶ If a device doesn't work as it should, you may often see several possible reasons. Depending on what it really is, you need to take different actions.

▶ Again, a computer model allows you to check many things efficiently – for example:

  ▶ Could a certain effect (which you previously neglected) really be strong enough to explain your problem?

  ▶ Would the use of a modified component cure the problem? (Don't need to order and try it if the model says no, it wouldn't!)

  ▶ How sensitive are certain parameters? Would some design work only if you align components with microradian precision, for example?

Building Your Competence

▶ Technical competence implies a **qualitative and quantitative understanding of what happens inside your devices**.

▶ Modeling turns your attention to exactly that – much more than experimenting. (You may build 1000 lasers in the lab without ever seeing what causes certain phenomena.)

▶ You also want to **identify fundamental limitations and unavoidable trade-offs**. That is achieved with thinking, not with building or measuring.

▶ You can learn from **trying out many ideas**.
A computer model makes such attempts quick, safe and cheap. (You would hardly invest hours into rearranging a laser setup and realigning it just for curiosity.)

RP Photonics

New Ideas

▶ You can hope that next morning you will wake up with a great new idea for a design improvement, or new product or whatever, … … however, normally it doesn't work like that!

▶ In reality, new ideas often emerge after you have focused your mind on various things – for example,

- ▶ if you investigated some nasty effects with a model,
- ▶ if you realized the fundamental reason for some limitation, or
- ▶ if you noticed a remarkable pattern when comparing designs.

▶ **New ideas are more likely to emerge when working with models**, since that means dealing with what is going on inside.

RP PHOTONICS

Conclusions

▶ **A thorough understanding of what happens inside your lasers** is not just nice to have, but **indispensable for efficient work**.

▶ Computer models for laser devices can be used as powerful tools for acquiring a thorough understanding – essentially, by **realizing the transparent laser**.

▶ Working based on **blind flight, trial & error in the lab** etc. is **wasteful and unprofessional**.

▶ The use of computer models costs some money and time, but easily saves a multiple of what it costs.

▶ Therefore, the question is not whether you can afford to invest into computer modeling for laser development, but **whether you can afford *not* to do it**!

RP Photonics

Common Concerns (1)

▶ **Won't modeling be too difficult for me, or take too much time?**

  ▶ That might be, but what if the alternative means fishing in the dark, never understanding how things really work, wasting time and resources, etc.? In that situation, don't resign, but think as follows:

  ▶ The first question should be: **What is the more efficient approach** for your development project: working with a computer model or trying without a model and its benefits? (This depends on the circumstances.)

  ▶ If the answer is that modeling is required, the next question is:
  Who should do it?
  Maybe a colleague of you is better placed to take over this job.
  Or use a competent technical consultant (→ ask RP Photonics!)
  in order to get the benefits of modeling without doing it yourself.

  ▶ Keep in mind that high-quality modeling software comes with competent **technical support**. If you go for RP Photonics, support means general technical consultancy in that area! You are not let alone.

RP PHOTONICS

Common Concerns (2)

▶ **How can I know that my models will be realistic?**

  ▶ Well, models can indeed be unrealistic. However, if you develop them with care – possibly using competent technical support from the software developer – , you shouldn't have a problem there.

  ▶ **Be happy to find discrepancies**, don't consider these as accidents: After all, this means learning useful things – for example,

    ▶ that certain components are not what you thought they are, or

    ▶ that certain effects are more important than you believed.

Common Concerns (3)

▶ **How can I know that the software works correctly, and the components' data are correct?**

- ▶ Of course, you need a software which you can trust.
  Ideally, you know that it has been developed by a trustworthy expert with proven competence.

- ▶ You can (and should) build confidence by first analyzing and testing simpler configurations.

- ▶ Inaccuracies of component data are indeed not uncommon. However, not working with a computer model would not remove that problem! Often, a computer model can help you to check component data and to obtain more accurate data sets, or to find laser designs which react less sensitively to variations of certain parameters.

RP Photonics

Move Forward! (1)

If you have now decided that you want to **stop a blind flight** and start **making your product development efficient and faster**, you can **move forward as follows**:

▶ Identify the most important technical areas, depending on what exactly you are developing, e.g.

  ▶ laser resonator design

  ▶ laser dynamics (e.g. Q switching or pulse amplification)

  ▶ ultrashort pulse generation (mode locking, amplifier systems)

▶ Think about what exactly you would like to make transparent, and what kind of questions you would like to answer in order to make faster progress.

Move Forward! (2)

▶ If you want to get into modeling yourself, find out which supplier is most likely to provide suitable **powerful simulation and design software** and **competent, helpful technical support**.

▶ If you consider that approach as not efficient in your case, find out which technical consultant is most likely to provide **competent and reliable technical advice**.

▶ Admittedly, here I am biased, but consider to **contact RP Photonics**!

   ▶ Software: http://www.rp-photonics.com/software.html

   ▶ Consulting: http://www.rp-photonics.com/consulting.html