Complex Optical Modulation

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an extension of work done at UF for LIGO in 1997 by

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Motivation

Why use complex modulation?

- Objective:
  - Solve the sidebands on sidebands problem.
  - Reduce the number of modulators to reduce the optical losses
- Requirements:
  - Generate AM and PM with arbitrary waveforms at very high sampling frequencies

Current solution to the sidebands on sidebands problem

- Use a Mach-Zehnder interferometer with one modulator in each arm.
  - Effect: No cross coupling between the sidebands
  - BUT: Amplitude modulation at modulation frequencies

- Idea: Can we simulate this without physically separating the beams?

- Yes -> complex modulation

Complex modulation

- General representation for an amplitude- and phase modulated light field:

$$E(t) = \frac{E_0}{2} \exp(i\omega t + f(t)) + c.c.$$

- with

$$f(t) = i\phi(t) + \alpha(t)$$

- Question: which modulation is needed to generate a certain light field?

$$E_{new}(t) + c.c. = E_{old}(t) \times \exp(f(t)) + c.c.$$

- solving (easy without the + c.c.) leads to:

$$\phi(t) = arg\left(\frac{E_{new}(t)}{E_{old}(t)}\right) \qquad \alpha(t) = \ln\left|\frac{E_{new}(t)}{E_{old}(t)}\right|$$

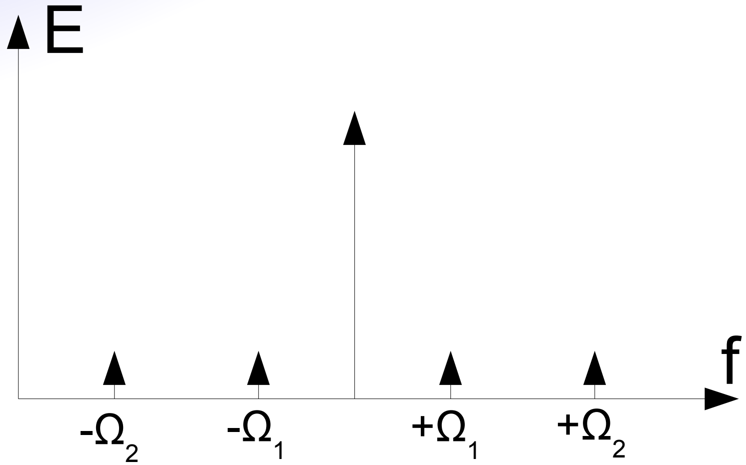
Example - Two sidebands without mixing terms

- We want two pairs of sidebands without mixing (and higher order) terms

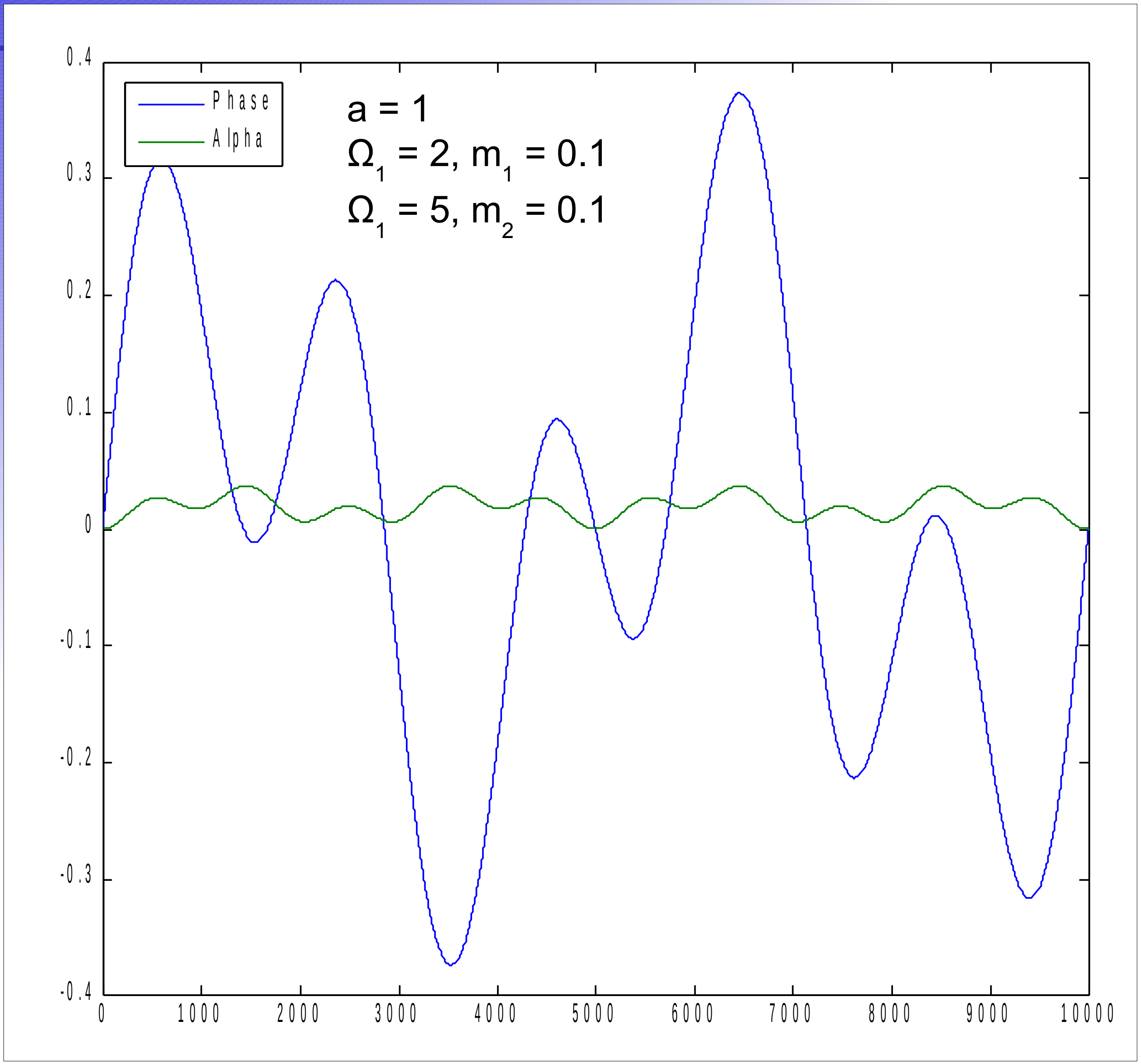
$$E(t)=\frac{E_0}{2}\exp(i\omega t)\times\left(a+m_1\mathrm{e}^{i\Omega_1 t}-m_1\mathrm{e}^{-i\Omega_1 t}+m_2\mathrm{e}^{i\Omega_2 t}-m_2\mathrm{e}^{-i\Omega_2 t}\right)+c.c.$$

Solution:

$$f(t)=\log\left(a+2i\,m_1\sin(\Omega_1 t)+2i\,m_1\sin(\Omega_2 t)\right)$$

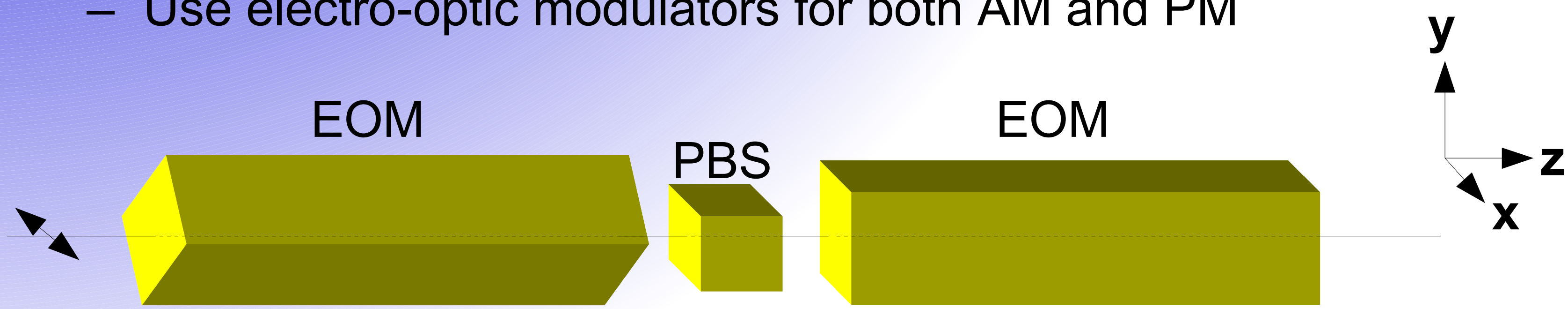


Example I - Two sidebands without mixing terms



Experimental realization I

- Sidebands at several ten MHz require fast phase and amplitude changes.
  - Use electro-optic modulators for both AM and PM



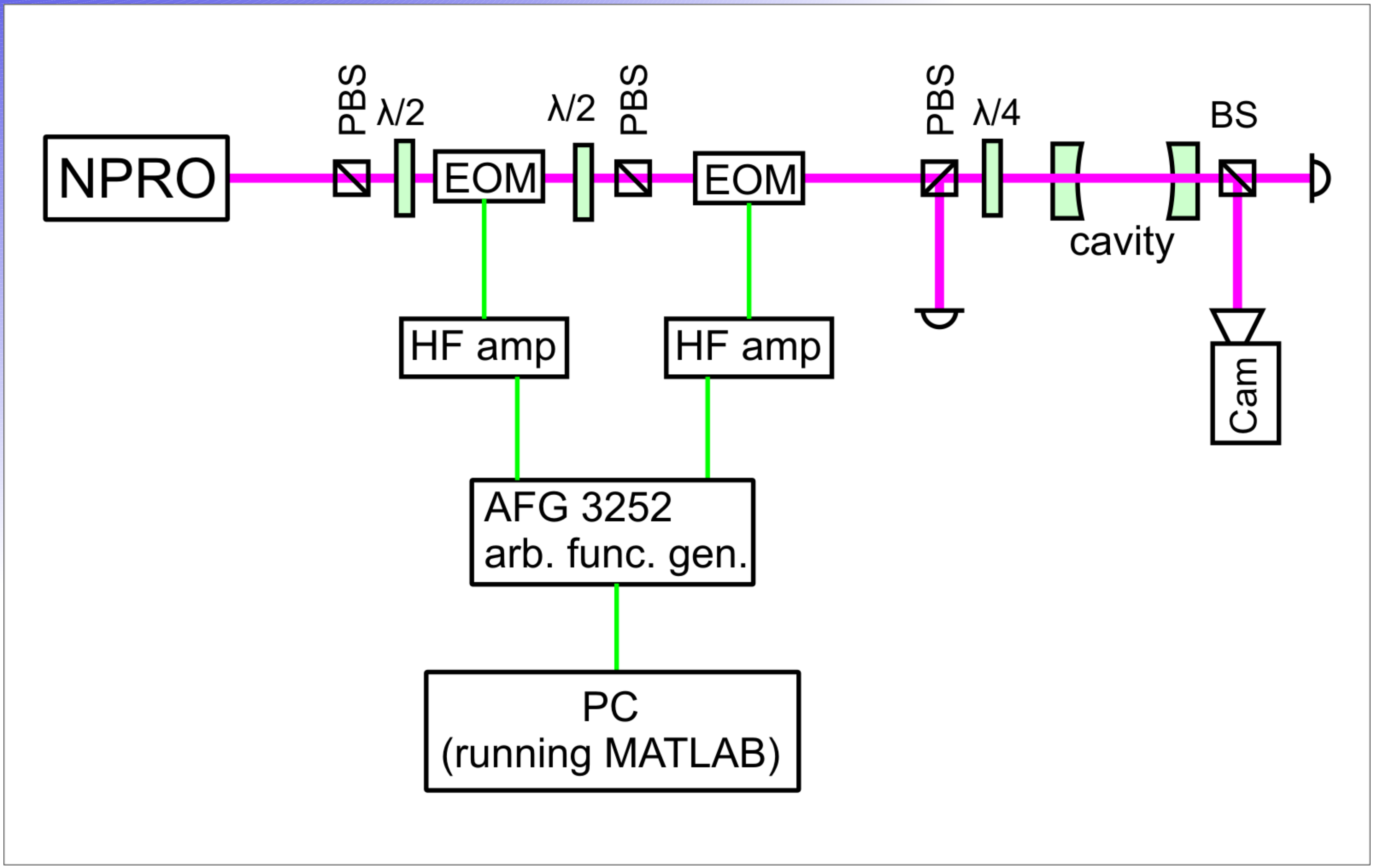
$$i\phi_a(t)+\alpha(t) \qquad\qquad i\phi_p(t)$$

- PM - (OK)
- AM - PM between polarizers (drawback: unwanted phase modulation)

- Creation of complex modulation is possible:

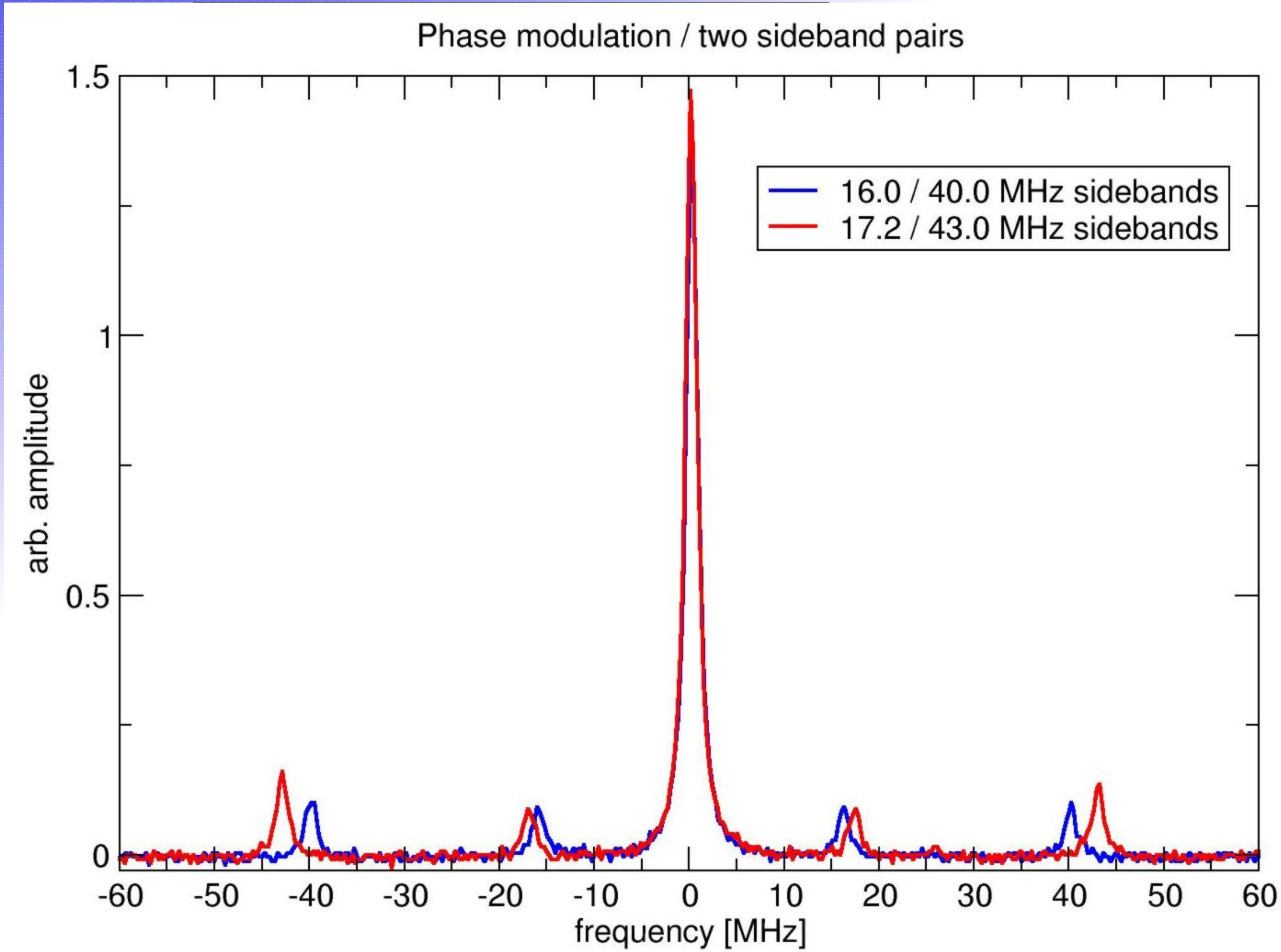
$$f(t)=i\phi_a(t)+i\phi_p(t)+\alpha(t)$$

Experimental setup



Two sidebands with one (phase) modulator

cross terms present, but not visible



Problems

The transfer function of the modulators has to be flat

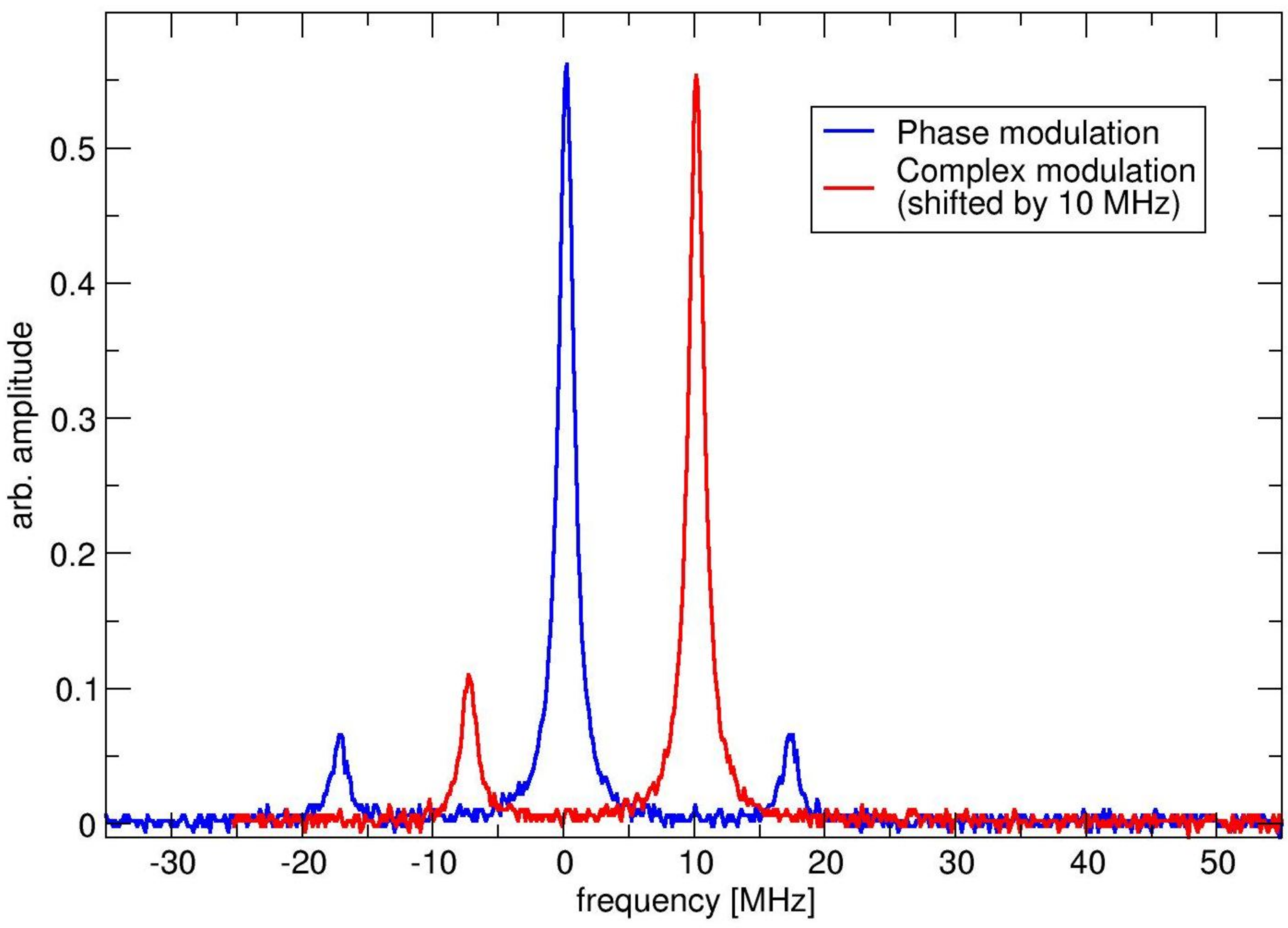
Three problems:

- Temperature dependent AM
- Resonances prohibit compensation of mixing terms
- The (current) HF amplifier get nonlinear for bigger driving signals

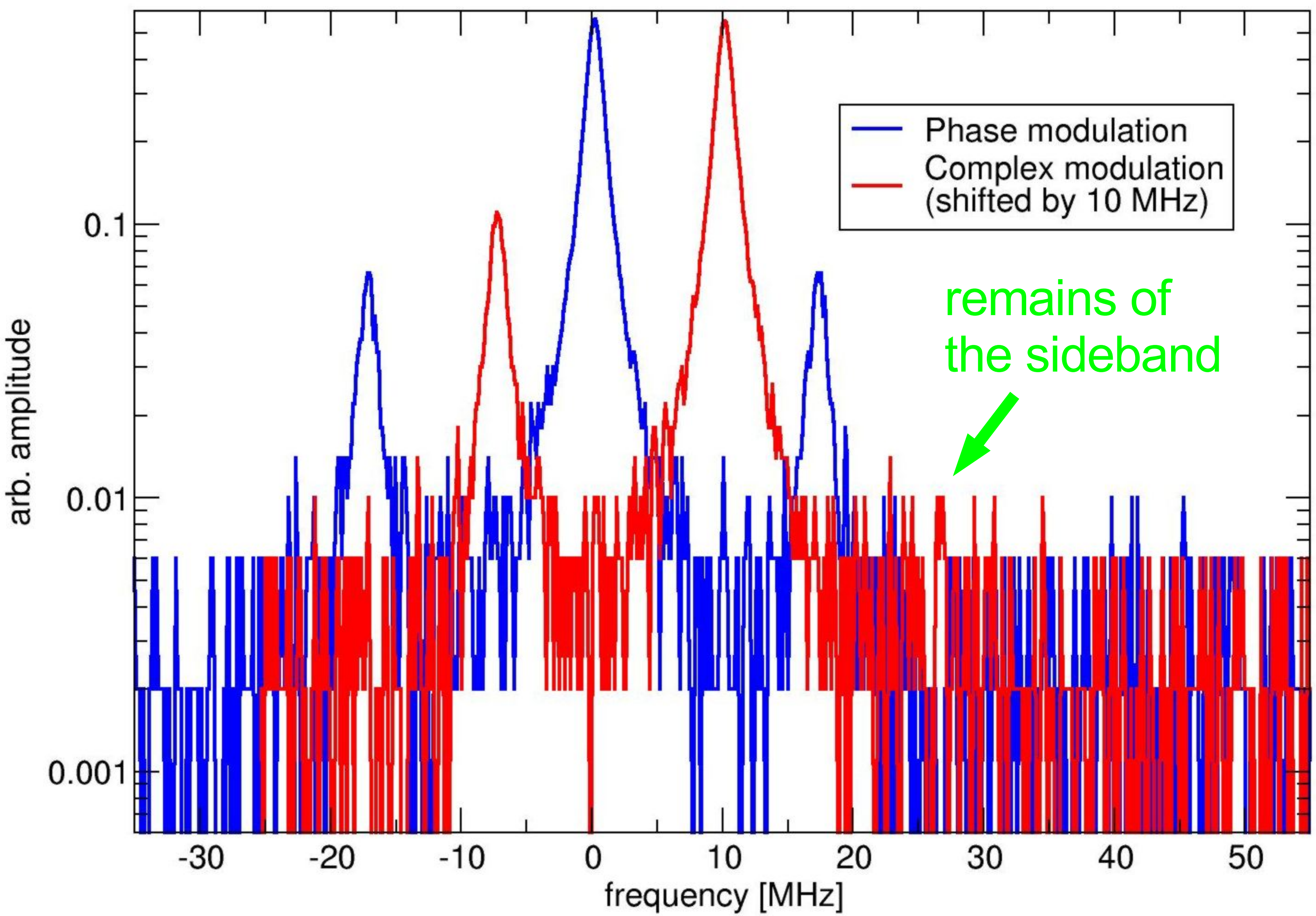
Encouraging first results

- Despite the current problems the setup is able to create and measure a single sideband on the carrier. (Possible because only one frequency component is needed)

Single sideband at 17 MHz



Single sideband at 17 MHz



Immediate plans / Conclusion

- Currently we are looking into ...
  - getting better HF amplifiers
  - damping the resonances in the modulators
  - setting up a temperature control for the amplitude modulators

- Theoretical investigations ...
  - Effect of highly dispersive interferometer transfer function on sidebands created with complex modulation.
    - Analytical calculations / Optickle simulation

- Preliminary conclusion:

  promising method to solve modulation problems

Two sidebands with one (phase) modulator

cross terms present, but not visible