Signal Extraction and Length Sensing for LIGO II RSE

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Caltech

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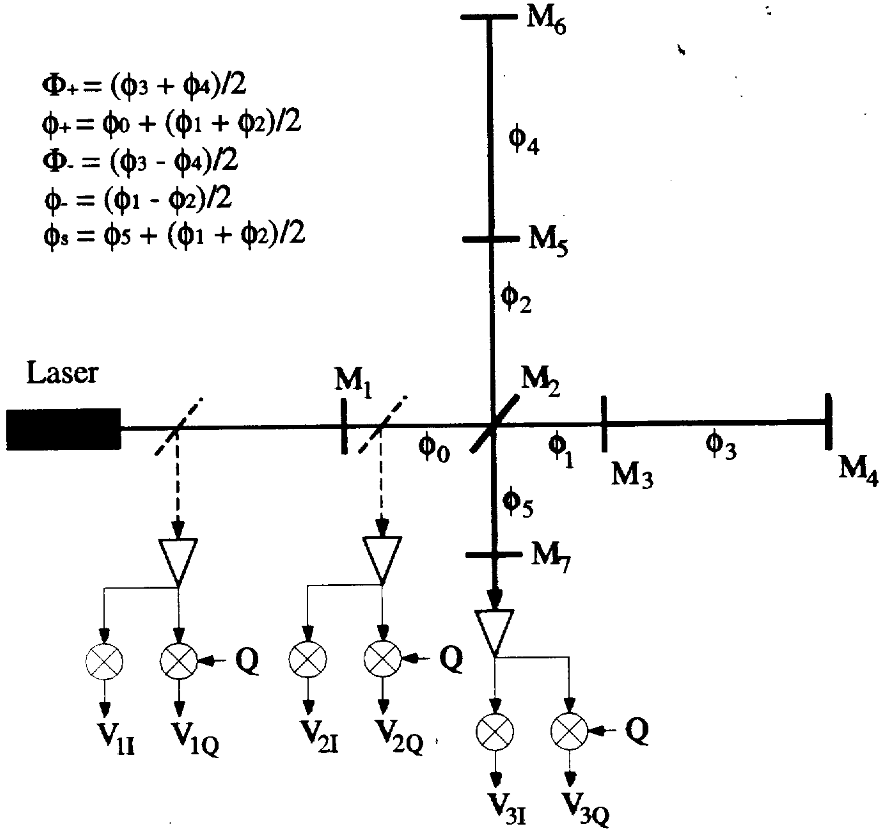
Resonant Sideband Extraction : The salient points



$\Phi_+ = (\phi_3 + \phi_4)/2$

$\phi_+ = \phi_0 + (\phi_1 + \phi_2)/2$

$\Phi_- = (\phi_3 - \phi_4)/2$

$\phi_- = (\phi_1 - \phi_2)/2$

$\phi_s = \phi_5 + (\phi_1 + \phi_2)/2$

- Higher arm cavity finesse, and detunable

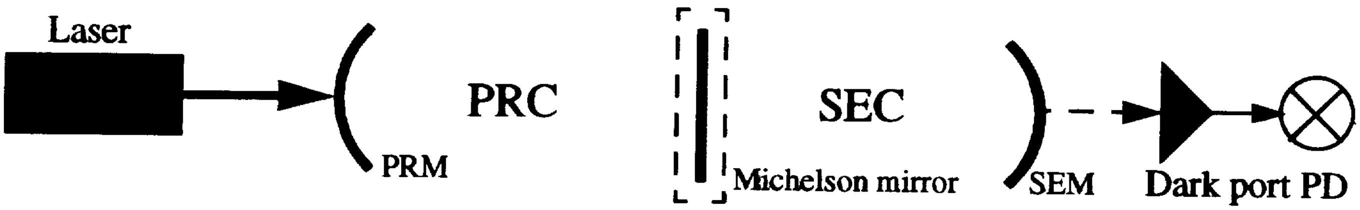
  — **Lower power recycling gain requirements, which leads to reduction of importance of thermal lensing and power loss in PRC**

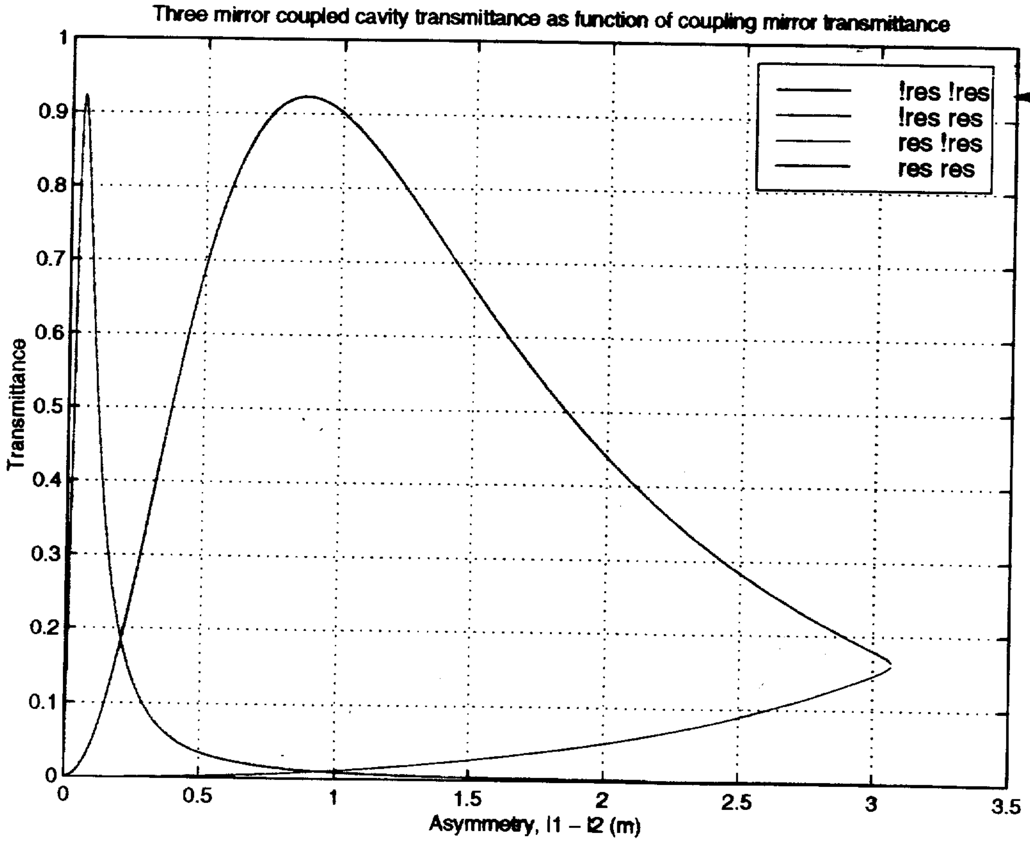
- RSE is well understood and verified for the relevant astrophysics
- Issues of control and signal extraction still remain

  ››It's a large parameter space!

What about the sidebands?

- LSC via optical heterodyne techniques
  - ››LIGO's paradigm : Frontal modulation
- How do the sidebands transmit to the dark port?
  - ››Sideband transmission is well approximated by coupled cavity transmission : PRC and SEC cavities.

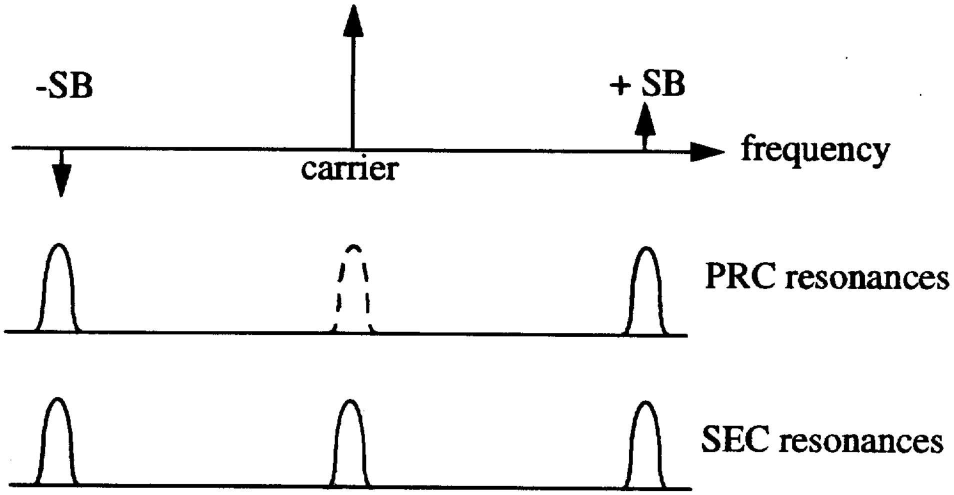



Three mirror coupled cavity transmittance as function of coupling mirror transmittance

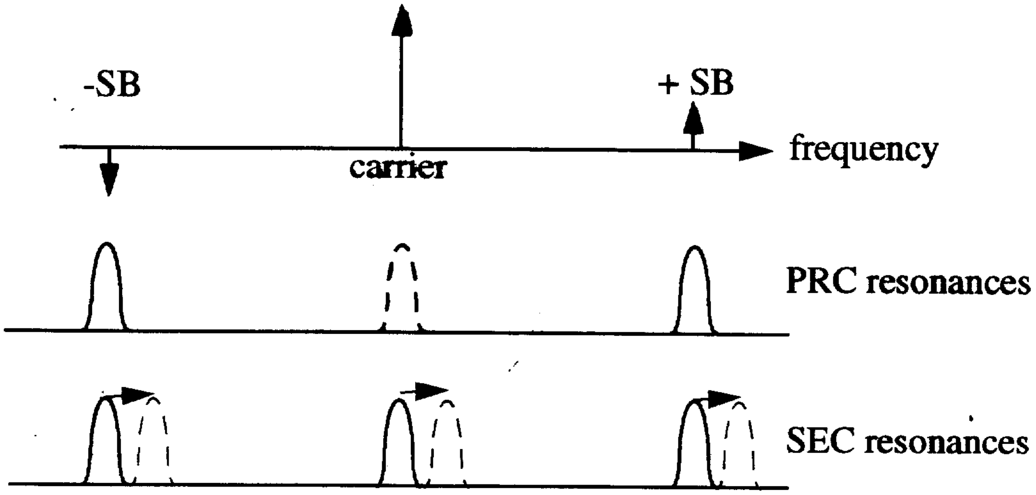
PRC/SEC resonance conditions

Detuning

- In broadband mode, high transmission for both sidebands
  - ››Symmetry of sidebands about carrier matches symmetry of FSR

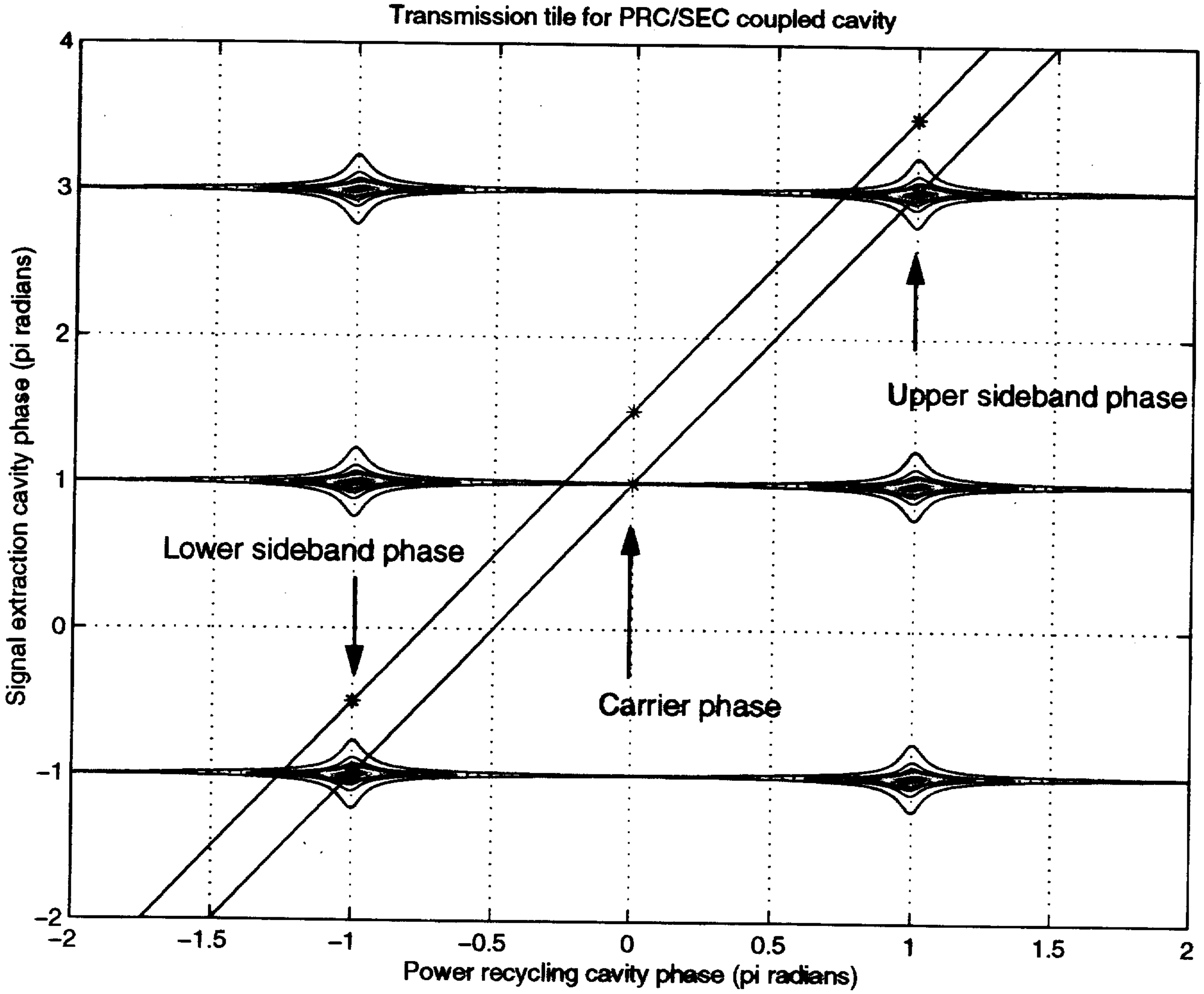


- Detuning introduces a problem
  - ››Both sidebands no longer resonant in coupled-cavity system



Detuning

- Loss of RF sideband transmission



››Slope is ratio of SEC length to PRC length

››For very small detunings, might be ok. Frequently, however; transmission drops to ~< 1%

Option 1 : SSB transmission

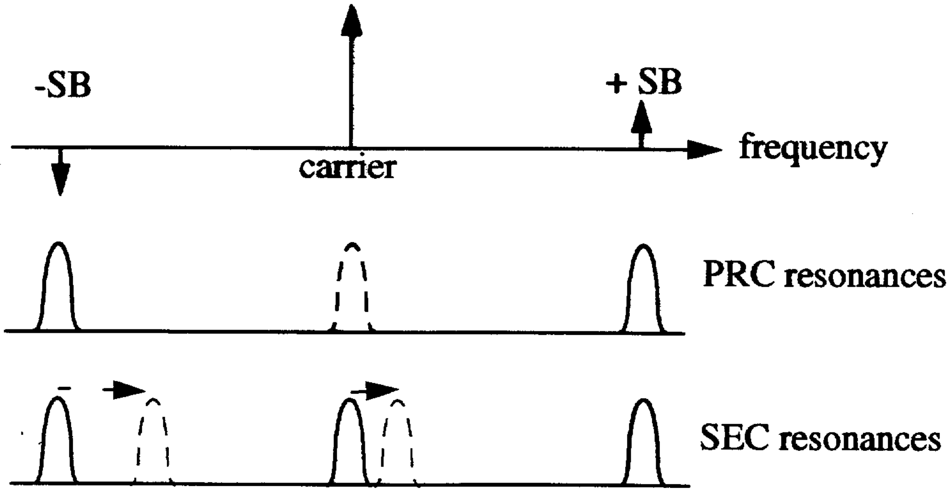
- Macroscopically detune to change slope of line to intersect region of high transmission

  ››Only one RF sideband gets out

  ››SEC length changes on the order of centimeters

  ››Once a macroscopic length change is made, there exists a range of microscopic detuning for which there is still significant RF sideband power transmitted to the dark port

  – **This can encompass the entire range of interest**



- Shot noise

  ››Signal reduced by factor of 2, but shot noise decreased by factor of sqrt(3), not sqrt(2)

  – **Cyclostationary process becomes stationary**

Twiddle RSE/SSB modeling (cont.)

››Detuned (high)

```
In[10]:= SetDirectory["/home/jim/rse/dynamic/twiddle_model/RSE"];
         IFOName = "rse_2";
         sborder = 2;
         << "twiddle.m"

    Twiddle version 3.0, February 1999

    Martin Regehr, James Mason, Hiro Yamamoto

    California Institute of Technology

    Proccessing rse_2_ifo.m

    Input Amplitudes = {0.109109 I, 0., 0.981981, 0.109109, 0.109109 I}

    Finished processing rse_2_ifo.m

    Matrix size is 35
```

- DOF 1 = Φ+, DOF 2 = Φ−. DOF 3 = ϕ+, DOF 4 = ϕ−, DOF 5 = ϕs

```
In[12]:= dof = {{m4, 1, m6, 1}, {m4, 1, m6, -1}, {m1, 1}, {m3, 1, m5, -1, m4, 1, m6, -1}, {m7, 1}};
         outindex = {index[m1, 1, 2], index[m1, 2, 1], index[bb1, 1, 1]};
         DCMatrix[dof, outindex, 0, mfreq, .001]
         DCMatrix[dof, outindex, 0, 2 mfreq / 3, .001]

    0 demodulation at 81. MHz

          DOF 1     DOF 2        DOF 3     DOF 4       DOF 5
    PD 1  -1732.53  0            0.628605  -0.0799628  -1.85177
    PD 2  -25009.6  -0.00249908  -7.32837  -3.91493    -90.6618
    PD 3  0         36.4747      0         0.0232362   0

    π
    - demodulation at 81. MHz
    2

          DOF 1     DOF 2       DOF 3      DOF 4        DOF 5
    PD 1  -88.4014  0           0.0375535  -0.827711    0
    PD 2  -442.006  -0.0258685  -0.637033  -40.5243     0.0196635
    PD 3  0         -1.84667    0          -0.00117642  0

    0 demodulation at 54. MHz

          DOF 1       DOF 2  DOF 3      DOF 4        DOF 5
    PD 1  -0.0012037  0      -0.112529  0            -1.99819
    PD 2  -0.012725   0      0.877946   -0.00669686  -19.0564
    PD 3  0           0      0          0.00518958   0
```

Twiddle RSE/SSB modeling

››Broadband

```
In[2]:= SetDirectory["/home/jim/rse/dynamic/twiddle_model/RSE"];
        IFOName = "rse_2";
        sborder = 2;
        << "twiddle.m"

        Twiddle version 3.0, February 1999

        Martin Regehr, James Mason, Hiro Yamamoto

        California Institute of Technology

        Proccessing rse_2_ifo.m

        Input Amplitudes = {0.109109 I, 0., 0.981981, 0.109109, 0.109109 I}

        Finished processing rse_2_ifo.m

        Matrix size is 35
```

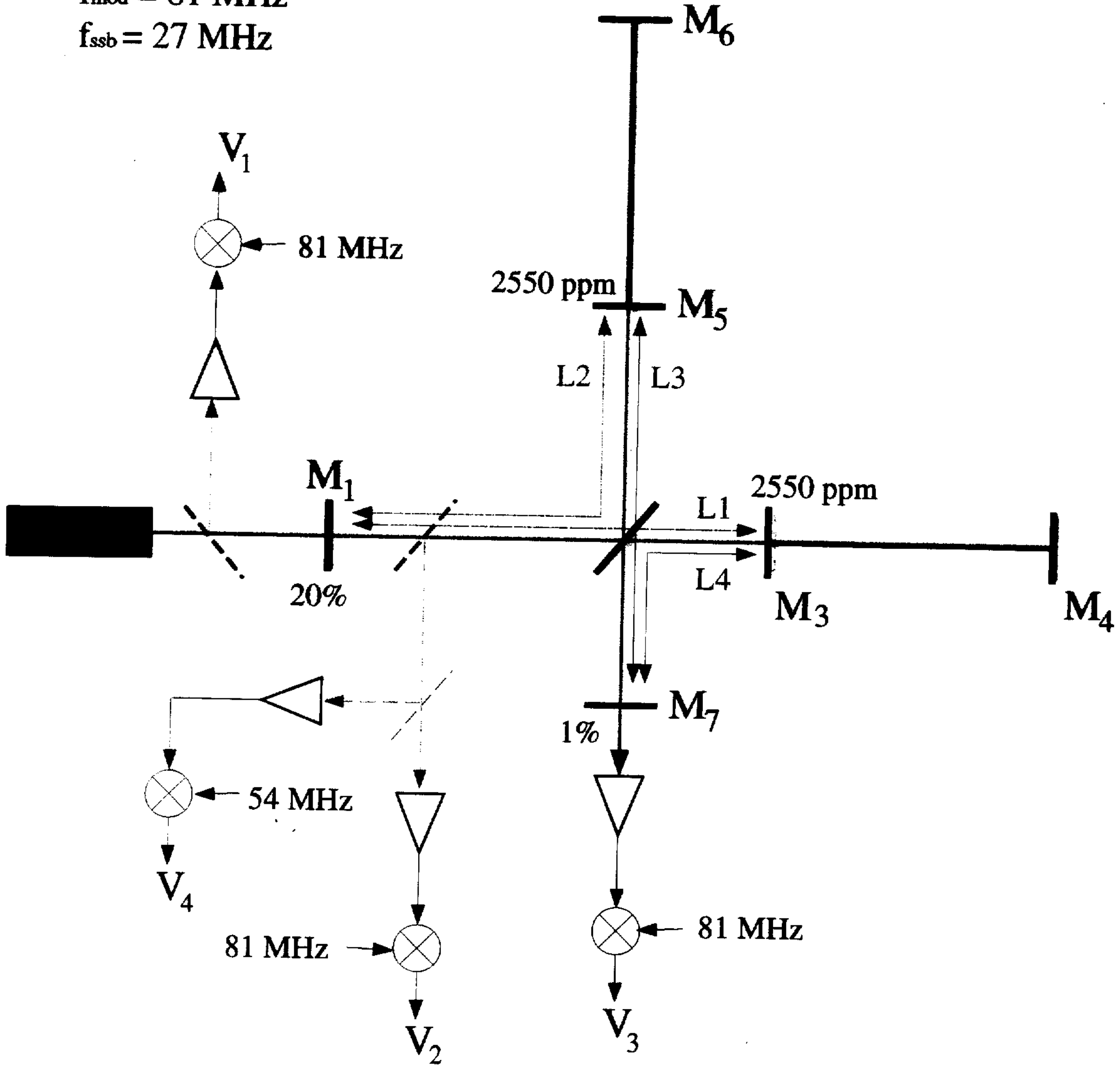
- DOF 1 = Φ+, DOF 2 = Φ−, DOF 3 = ϕ+, DOF 4 = ϕ−, DOF 5 = ϕs

```
In[4]:= dof = {{m4, 1, m6, 1}, {m4, 1, m6, -1}, {m1, 1}, {m3, 1, m5, -1, m4, 1, m6, -1}, {m7, 1}};
        outindex = {index[m1, 1, 2], index[m1, 2, 1], index[bb1, 1, 1]};
        DCMatrix[dof, outindex, 0, mfreq, .001]
        DCMatrix[dof, outindex, 0, 2 mfreq / 3, .001]

        0 demodulation at 81. MHz

              DOF 1      DOF 2   DOF 3     DOF 4       DOF 5
        PD 1  129.676    0       -0.2639   0           -3.71199
        PD 2  -15698.6   0       1.12496   0           -181.737
        PD 3  0          72.631  0         0.0462697   0

        π/2 demodulation at 81. MHz

              DOF 1  DOF 2         DOF 3  DOF 4     DOF 5
        PD 1  0      -0.00104935   0      -1.64386  0
        PD 2  0      -0.0513756    0      -80.4824  0
        PD 3  0      0             0      0         0

        0 demodulation at 54. MHz

              DOF 1       DOF 2  DOF 3      DOF 4        DOF 5
        PD 1  -0.0012037  0      -0.112529  0            -1.99819
        PD 2  -0.012725   0      0.877945   -0.00739581  -19.0564
        PD 3  0           0      0          0.00531049   0
```

RSE - SSB method

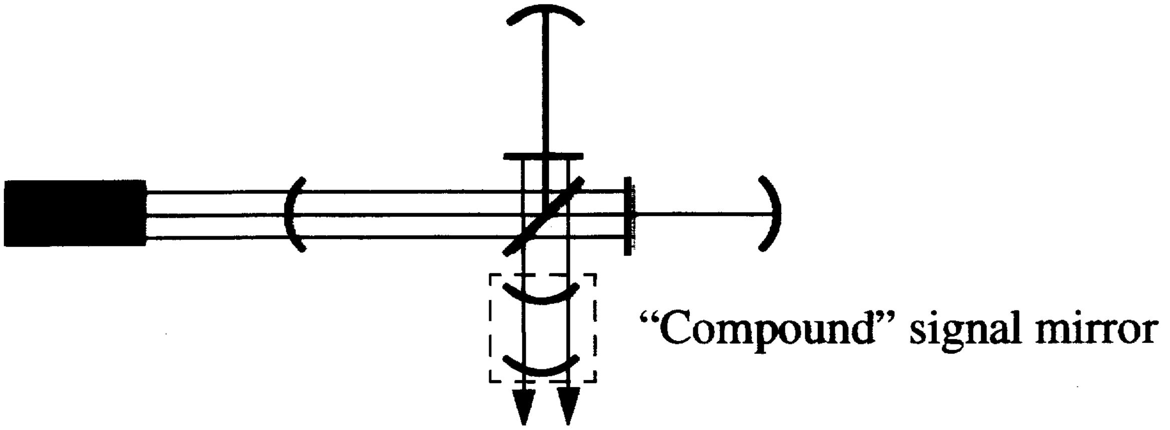
$L_{PRC\,avg} = (L1 + L2)/2 = 2.776\text{m}.$
$L_{SEC\,avg} = (L3 + L4)/2 = 1.804 - 1.851\ \text{m}.$
$\delta = (L2 - L1) = 1.55\ \text{cm}.$

$f_{mod} = 81\ \text{MHz}$
$f_{ssb} = 27\ \text{MHz}$



Option 2 : OCC

- Replace SEM with an Output Coupling Cavity
  - **Make the cavity (nearly) optimally coupled on resonance**
  - **Resonate the RF sidebands**
  - **Anti-resonate the carrier, choose mirrors T1~T2 such that the transmittance at anti-resonance is the desired transmittance for the SEM**



- High transmission for all detunings

  ››OCC makes the SEC "invisible" for RF sidebands
- Microscopic (fractional λ) detuning of SEC
- Shot noise

  ››Recovers the standard shot noise result (3/2 times the sideband power).

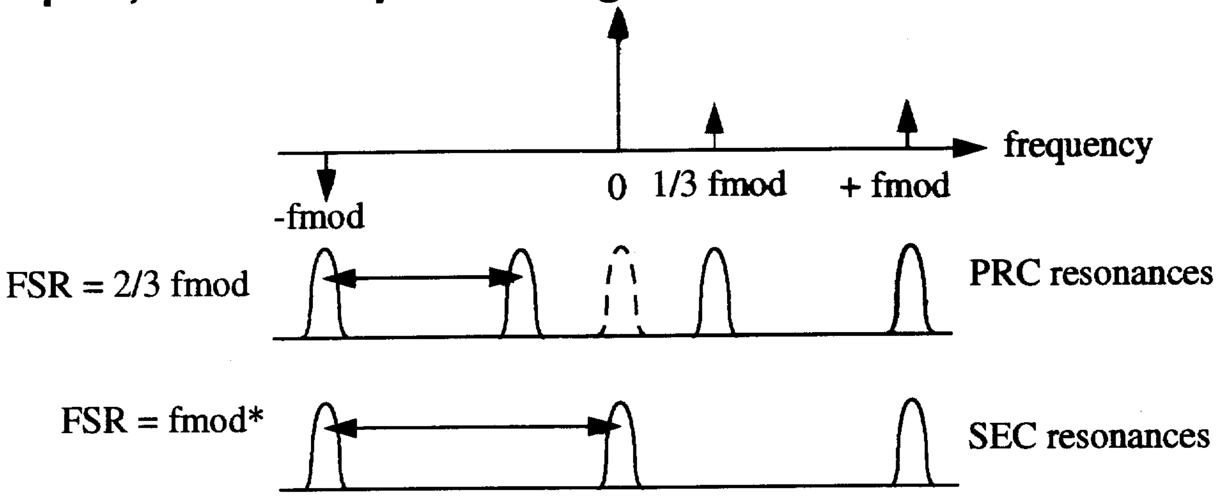
  ››OCC better than SSB by factor of 2/sqrt(3) (wow!)

Length control : SSB

- Need an independent LO to measure RF sideband phase variation in SEC

  ››Add subcarrier at fmod/3 or some integral odd fraction of fmod

  — Taken as a constraint that all frequencies are integer multiples, in order to pass through a mode cleaner



››Use [fmod-fmod/3] beatnote at existing signal ports (PRC pickoff, for example) for control of SEC

››Control signal for SEC independent of detuning

››Control signals for all other d.o.f. not

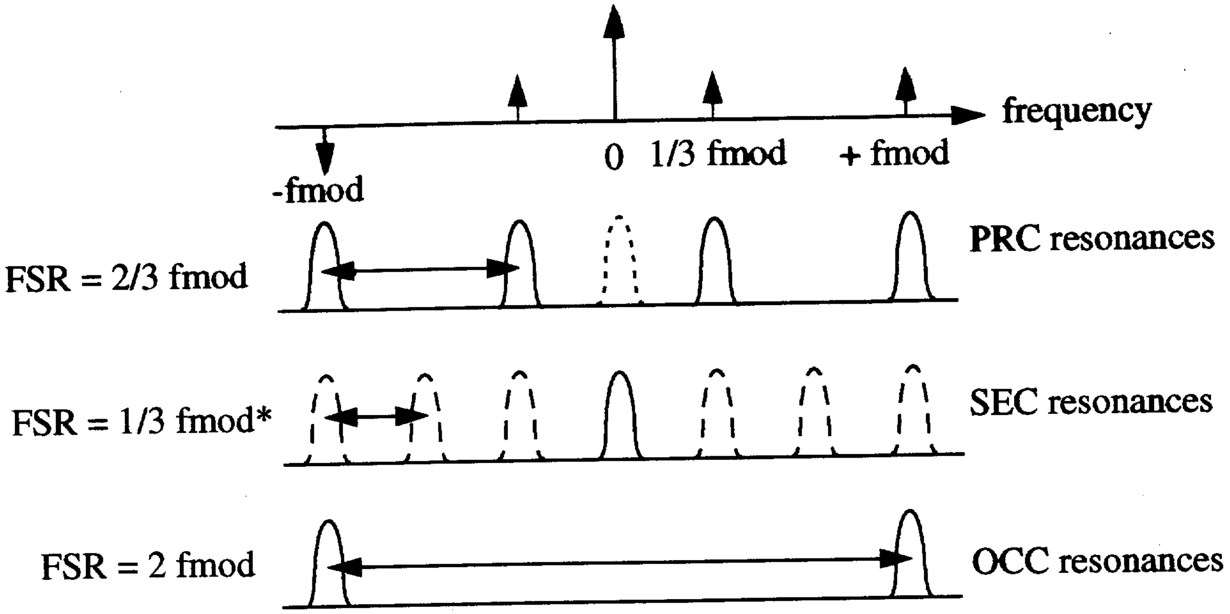
— Strong cross-couplings when weakly detuned

— Less bothersome when highly detuned, however, signal gains tend to change significantly (~ order of magnitude)

Length Control : OCC

- 2 additional d.o.f.

  ››~ same idea as SSB, except add two AM sidebands at integral odd fractions of fmod.



››New pickoff at first OCC mirror -> new signal port

- **Beatnote clearly gives signal for OCC cavity at this port**
- **Beatnote at prc cavity port still gives SEC signal**
- **Diagonal!**

››Std. d.o.f. signals now only very weakly dependent on detuning

››Add'l d.o.f. signals can have detuning dependence. However, in many designs, it's also quite weak.

Twiddle RSE/OCC modeling

››Broadband

```
In[14]:= SetDirectory["/home/jim/rse/dynamic/twiddle_model/OCC"];
         IFOName = "occ";
         sborder = 2;
         << "twiddle.m"

      Twiddle version 3.0, February 1999

      Martin Regehr, James Mason, Hiro Yamamoto

      California Institute of Technology

      Proccessing occ_ifo.m

      Input Amplitudes = {0.108465 I, 0.108465, 0.976187, 0.108465, 0.108465 I}

      Finished processing occ_ifo.m

      Matrix size is 39
```

- DOF 1 = Φ+, DOF 2 = Φ−, DOF 3 = ϕ+, DOF 4 = ϕ−, DOF 5 = ϕs, DOF 6 = ϕocc

```
In[15]:= dof = {{m4, 1, m6, 1}, {m4, 1, m6, -1},
            {m1, 1}, {m3, 1, m5, -1, m4, 1, m6, -1}, {m7, 1, m8, 1}, {m8, 1}};
         outindex = {index[m1, 1, 2], index[m1, 2, 1], index[m7, 1, 2], index[bb1, 1, 1]};
         DCMatrix[dof, outindex, 0, mfreq, .001]
         DCMatrix[dof, outindex, 0, mfreq - mfreq2, .06]

      0 demodulation at 81. MHz

            DOF 1      DOF 2      DOF 3       DOF 4        DOF 5       DOF 6
      PD 1  -72.4557   0          -0.154366   0            0           0.214745
      PD 2  -16516.9   0          0.704547    0            0.0248844   10.5138
      PD 3  0          -9.14629   0           -0.00582665  0           0
      PD 4  0          0          0           0            0           0

      π
      ─ demodulation at 81. MHz
      2

            DOF 1  DOF 2        DOF 3  DOF 4       DOF 5  DOF 6
      PD 1  0      0            0      -0.0966022  0      0
      PD 2  0      -0.00301912  0      -4.72959    0      0
      PD 3  0      0            0      0           0      0
      PD 4  0      77.3161      0      0.0492543   0      0

      0 demodulation at 54. MHz

            DOF 1  DOF 2  DOF 3      DOF 4       DOF 5     DOF 6
      PD 1  0      0      0.17445    0           0         -0.187301
      PD 2  0      0      -0.298487  1.34557     1.53639   0.210187
      PD 3  0      0      0          0           0         0.645564
      PD 4  0      0      0          -0.0630923  0         0
```

Twiddle RSE/OCC modeling

››Detuned

```
SetDirectory["/home/jim/rse/dynamic/twiddle_model/OCC"];
IFOName = "occ";
sborder = 2;
<< "twiddle.m"
```

```
Twiddle version 3.0, February 1999

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Proccessing occ_ifo.m

Input Amplitudes = {0.108465 I, 0.108465, 0.976187, 0.108465, 0.108465 I}

Finished processing occ_ifo.m

Matrix size is 39
```

- DOF 1 = Φ+, DOF 2 = Φ−, DOF 3 = ϕ+, DOF 4 = ϕ−, DOF 5 = ϕs, DOF 6 = ϕocc

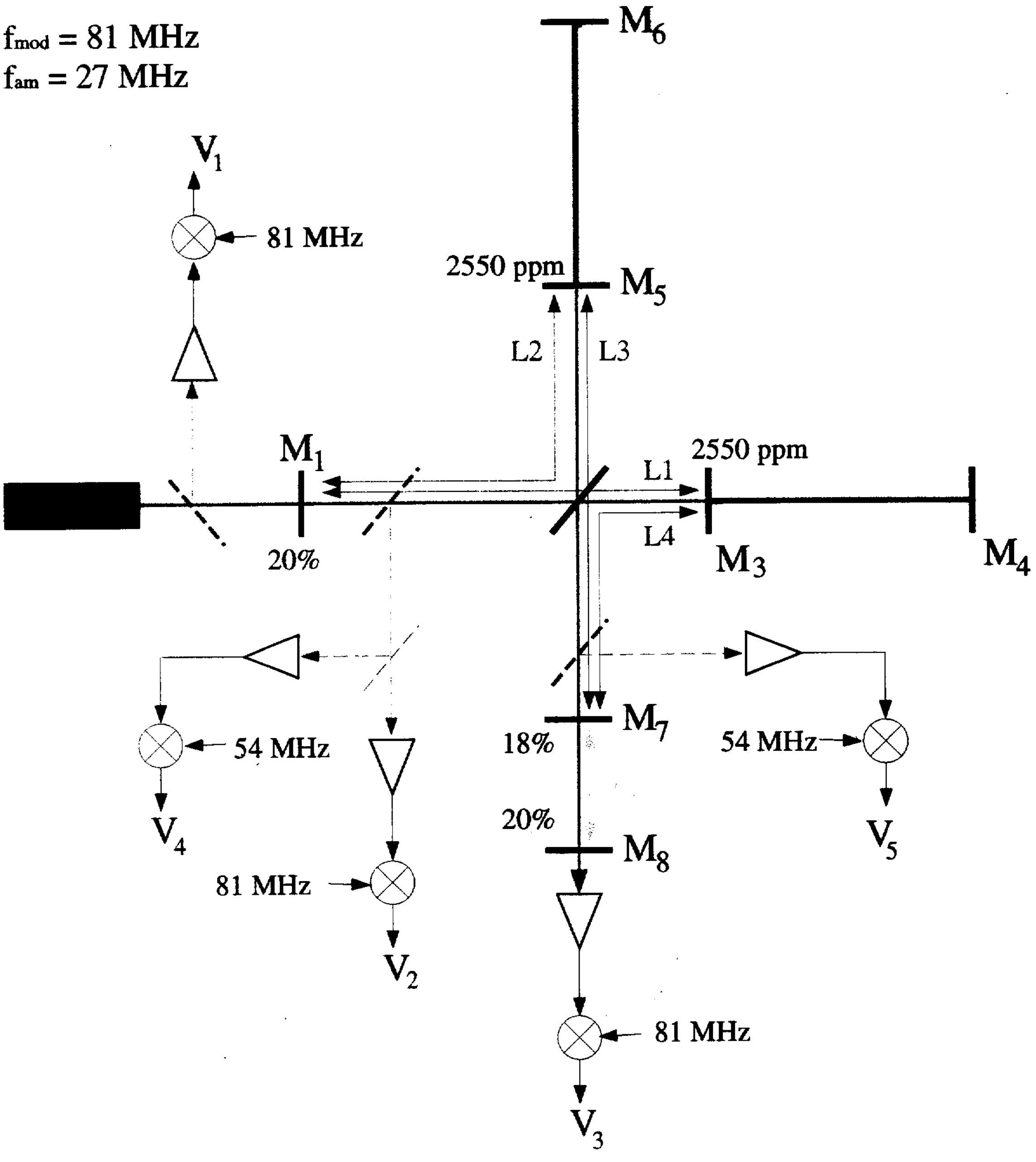
```
dof = {{m4, 1, m6, 1}, {m4, 1, m6, -1},
   {m1, 1}, {m3, 1, m5, -1, m4, 1, m6, -1}, {m7, 1, m8, 1}, {m8, 1}};
outindex = {index[m1, 1, 2], index[m1, 2, 1], index[m7, 1, 2], index[bb1, 1, 1]};
DCMatrix[dof, outindex, 0, mfreq, .001]
DCMatrix[dof, outindex, 0, mfreq - mfreq2, .06]
```

```
0 demodulation at 81. MHz

      DOF 1     DOF 2     DOF 3      DOF 4        DOF 5     DOF 6
PD 1  -72.4019  0         -0.154394  0            0         0.214474
PD 2  -16516.6  0         0.704667   0            0.024853  10.5005
PD 3  0         -9.14656  0          -0.00582682  0         0
PD 4  0         0         0          0            0         0

π
─ demodulation at 81. MHz
2

      DOF 1  DOF 2        DOF 3  DOF 4       DOF 5  DOF 6
PD 1  0      0            0      -0.0966023  0      0
PD 2  0      -0.00301912  0      -4.7296     0      0
PD 3  0      0            0      0           0      0
PD 4  0      77.3184      0      0.0492558   0      0

0 demodulation at 54. MHz

      DOF 1  DOF 2  DOF 3      DOF 4       DOF 5     DOF 6
PD 1  0      0      0.23129    -0.120208   0         -0.173559
PD 2  0      0      -0.341887  0.865898    2.11724   0.303424
PD 3  0      0      -0.322365  -0.859629   -0.17476  0.61558
PD 4  0      0      0          -0.0654685  0         0
```

RSE - OCC method

$L_{PRC\,avg} = (L1 + L2)/2 = 2.776$ m.
$L_{SEC\,avg} = (L3 + L4)/2 = 1.851$ m.
$L_{OCC} = 0.925$ m.
$\delta = 1.55$ cm.

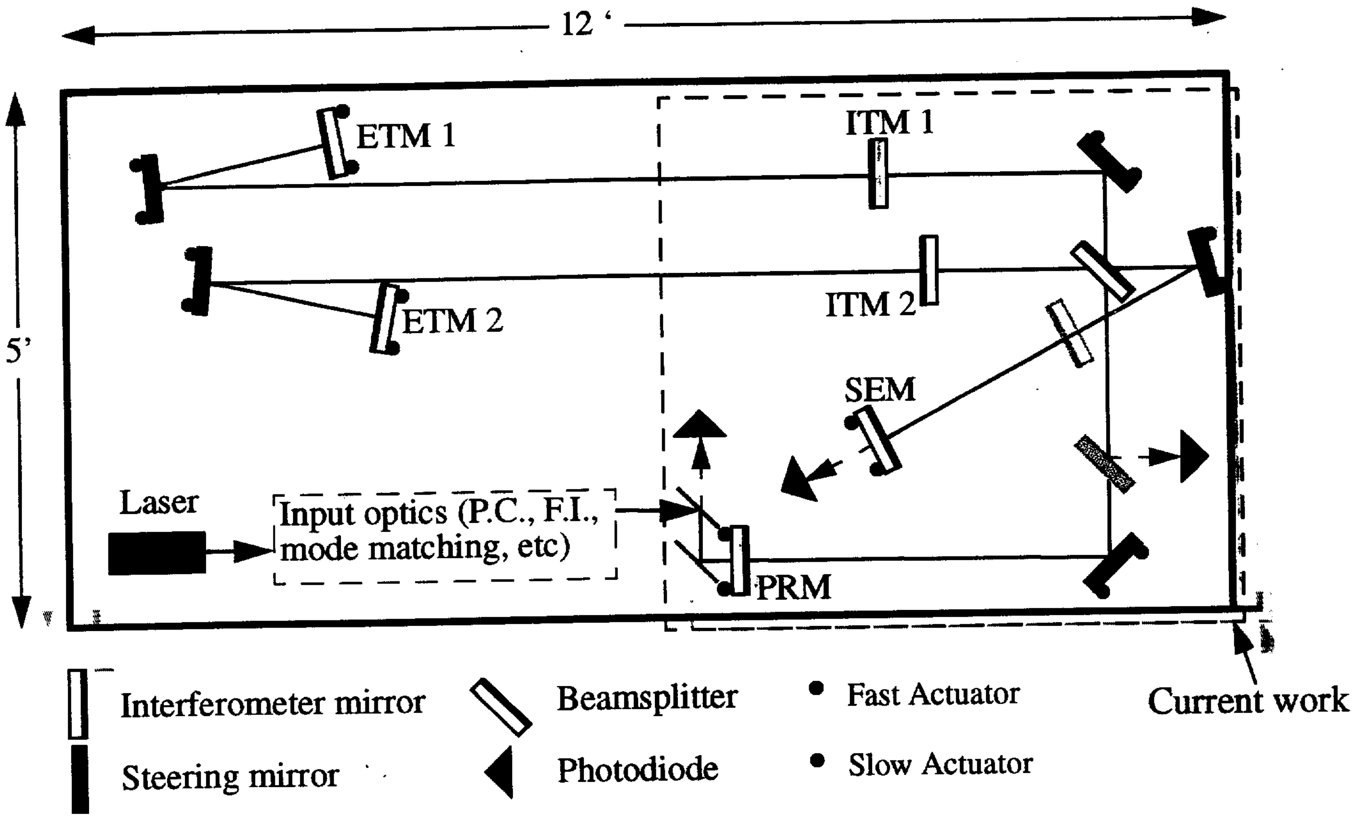
$f_{mod} = 81$ MHz
$f_{am} = 27$ MHz



Experimental Work (in progress)

- Goals :

››To implement both SSB and OCC schemes, and demonstrate the relative pros and cons of each method



››Power recycled-arm cavity characterized (arm finesse ~ 1000)

››Power recycled Michelson and Signal recycled Michelson also done

››Dual Recycled Michelson locked, but still work to be done

Note 1, Linda Turner, 08/17/99 08:13:04 PM

LIGO-G990079-23-M