Enhancing sensitivity of gravitational wave antennas, such as LIGO, via light-atom interaction

Eugeni E. Mikhailov

The College of William & Mary, USA

New Laser Scientists, 24 October 2014
- \( L = 4 \text{ km} \)
- \( h \sim 2 \times 10^{-23} \)
- \( \Delta L \sim 10^{-20} \text{ m} \)
LIGO sensitivity, S5 run, June 2006

Strain Sensitivity for the LIGO Interferometers

S5 Performance - June 2006 LIGO-G060293-02-Z

Inspiral search range during S5 is 14Mpc
Eugeniy E. Mikhailov (W&M)
Upgrade to advanced LIGO

Goals

- Factor of 15 increase in sensitivity
- Inspiral range from 20 Mpc to 350 Mpc
- Factor of 3000 in event rate
  One day > entire 2-year initial data run

How

- Better seismic isolation
- Decreasing thermal noise
- Higher laser power
- Injection of squeezed state
Squeezed quantum states zoo

Unsqueezed coherent

Amplitude squeezed

Phase squeezed

Vacuum squeezed

Eugeniy E. Mikhailov (W&M)
Squeezed quantum states zoo

Unsqueezed coherent

Amplitude squeezed
Squeezed quantum states zoo

- Unsqueezed coherent
- Amplitude squeezed
- Phase squeezed
Squeezed quantum states zoo

Unsqueezed coherent

Amplitude squeezed

Phase squeezed

Vacuum squeezed

Eugeniy E. Mikhailov (W&M)

Sensitivity boost with light-atom interaction

New Laser Scientists, 2014
Squeezing and interferometer

Vacuum input
Squeezing and interferometer

Vacuum input

Squeezed input

Sensitivity boost with light-atom interaction

New Laser Scientists, 2014 14 / 28
Next generation of LIGO will be quantum optical noise limited at almost all detection frequencies.

**shot noise**

Uncertainty in number of photons

\[ h \sim \sqrt{\frac{1}{P}} \]  \hspace{1cm} (1)
Next generation of LIGO will be \textit{quantum optical noise limited} at almost all detection frequencies.

\begin{align*}
\text{shot noise} & : \text{Uncertainty in number of photons} \\
\ h \sim \sqrt{\frac{1}{P}} & \quad (1) \\
\text{radiation pressure noise} & : \text{Photons impart momentum to mirrors} \\
\ h \sim \sqrt{\frac{P}{M^2 f^4}} & \quad (2)
\end{align*}
Next generation of LIGO will be quantum optical noise limited at almost all detection frequencies.

**shot noise**
Uncertainty in number of photons

\[ h \sim \sqrt{\frac{1}{P}} \]  \hspace{1cm} (1)

**radiation pressure noise**
Photons impart momentum to mirrors

\[ h \sim \sqrt{\frac{P}{M^2 f^4}} \]  \hspace{1cm} (2)

There is no optimal light power to suit all detection frequency. Optimal power depends on desired detection frequency.
Interferometer sensitivity improvement with squeezing

Projected advanced LIGO sensitivity

Squeezing and detection noise quadratures

\[ X^2 - X^1 \theta \]

Noise vs quadrature angle

Eugeniy E. Mikhailov (W&M)
 Electromagnetically Induced Transparency (EIT) filter

![Graph showing probe transparency dependence on its detuning.](image)

|b⟩

|c⟩

|a⟩

ω_p

ω_{bc}
Electromagnetically Induced Transparency (EIT) filter

Probe transparency dependence on its detuning.

| a ⟩
| b ⟩
| c ⟩

ω_p
ω_d
ω_{bc}

Transparency [Arb. Unit]
0 0.2 0.4 0.6 0.8 1
-100 -50 0 50 100
Probe detuning [Arb. Unit]

Transparency [Arb. Unit]
0 0.2 0.4 0.6 0.8 1
-100 -50 0 50 100
Probe detuning [Arb. Unit]
Squeezing and EIT filter

\[
\begin{pmatrix}
V_{1}^{\text{out}} \\
V_{2}^{\text{out}}
\end{pmatrix} =
\begin{pmatrix}
A_{+}^{2} & A_{-}^{2} \\
A_{-}^{2} & A_{+}^{2}
\end{pmatrix}
\begin{pmatrix}
V_{1}^{\text{in}} \\
V_{2}^{\text{in}}
\end{pmatrix} + 
\left[ 1 - (A_{+}^{2} + A_{-}^{2}) \right]
\begin{pmatrix}
1 \\
1
\end{pmatrix}
\]

\[
A_{\pm} = \frac{1}{2} \left( T_{+} \pm T_{-} \right)
\]
Squeezing and EIT filter

\[
\begin{pmatrix}
V_{1}^{out} \\
V_{2}^{out}
\end{pmatrix} = \begin{pmatrix}
A_+^2 & A_-^2 \\
A_-^2 & A_+^2
\end{pmatrix} \begin{pmatrix}
V_{1}^{in} \\
V_{2}^{in}
\end{pmatrix} + \left[ 1 - (A_+^2 + A_-^2) \right] \begin{pmatrix}
1 \\
1
\end{pmatrix}
\]

\[A_\pm = \frac{1}{2}(T_+ \pm T_-)\]
Squeezing and EIT filter

\[
\begin{pmatrix}
V_{\text{out}1} \\
V_{\text{out}2}
\end{pmatrix} = \begin{pmatrix}
A_+^2 & A_-^2 \\
A_-^2 & A_+^2
\end{pmatrix} \begin{pmatrix}
V_{\text{in}1} \\
V_{\text{in}2}
\end{pmatrix} + \left[1 - (A_+^2 + A_-^2)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}
\]

\[
A_{\pm} = \frac{1}{2}(T_+ \pm T_-)
\]
Squeezing and EIT filter

\[
\begin{pmatrix}
V_{1}^{\text{out}} \\
V_{2}^{\text{out}}
\end{pmatrix} = \begin{pmatrix}
A_{+}^{2} & A_{-}^{2} \\
A_{-}^{2} & A_{+}^{2}
\end{pmatrix} \begin{pmatrix}
V_{1}^{\text{in}} \\
V_{2}^{\text{in}}
\end{pmatrix} + \left[1 - (A_{+}^{2} + A_{-}^{2})\right] \begin{pmatrix}
1 \\
1
\end{pmatrix}
\]

\[A_{\pm} = \frac{1}{2} (T_{+} \pm T_{-})\]

![Diagram of light-atom interaction](image)
Squeezing and EIT filter setup
Squeezing and EIT filter setup
EIT filter and measurements without light

Coherent signal

Signal in the noise quadratures
Wide EIT filter and squeezing

- Peak transmission = 52%
- FWHM= 4MHz

Input anti-squeezed noise
Calculated anti-squeezed
Input squeezed noise
Calculated squeezed noise
Measured squeezed noise
Measured anti-squeezed
Calculated squeezed noise
Input squeezed noise
Narrow EIT filter and squeezing

- Peak transmission = 50%
- FWHM = 2MHz

---

- Input anti-squeezed noise
- Calculated anti-squeezed
- Measured anti-squeezed
- Measured squeezed noise
- Calculated squeezed noise
- Input squeezed noise

---

Squeezing angle rotation

\[
\begin{pmatrix}
V_{out}^1 \\
V_{out}^2
\end{pmatrix} =
\begin{pmatrix}
\cos^2 \varphi_+ & \sin^2 \varphi_+ \\
\sin^2 \varphi_+ & \cos^2 \varphi_+
\end{pmatrix}
\begin{pmatrix}
A_+^2 & A_-^2 \\
A_-^2 & A_+^2
\end{pmatrix}
\begin{pmatrix}
V_{in}^1 \\
V_{in}^2
\end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right]
\begin{pmatrix}
1 \\
1
\end{pmatrix}
\]

Locked at 300kHz

Locked at 1200kHz

Sensitivity boost with light-atom interaction

Eugeniy E. Mikhailov (W&M)

New Laser Scientists, 2014 26 / 28
Summary

It is possible to boost sensitivity of gravitational wave antennas via light-atom interaction.

Proposed work

- narrow EIT resonance/filter
- maintain high transmission
- match squeezing filter to LIGO $\lambda = 1064$ nm
  - find atomic media which is resonant to 1064 nm
  - use existing methods to up convert atom-filtered squeezing $\lambda$ from 795 nm to 1064 nm