Quantum Sensing Laboratory Parts & Justification

Beyond fundamental quantum mechanics foundations experiments that have been incorporated into the "Quantum Mechanics for Computer Scientists" (COSC 210), the quantum industry also needs graduates who have an understanding of Applied Quantum Technologies (COSC 315), which can also be considered Quantum Sensing experiments.

As depicted in Fig. 1, there are multiple extraordinary quantum sensing experiments that will be available on a company platform (18"x24").

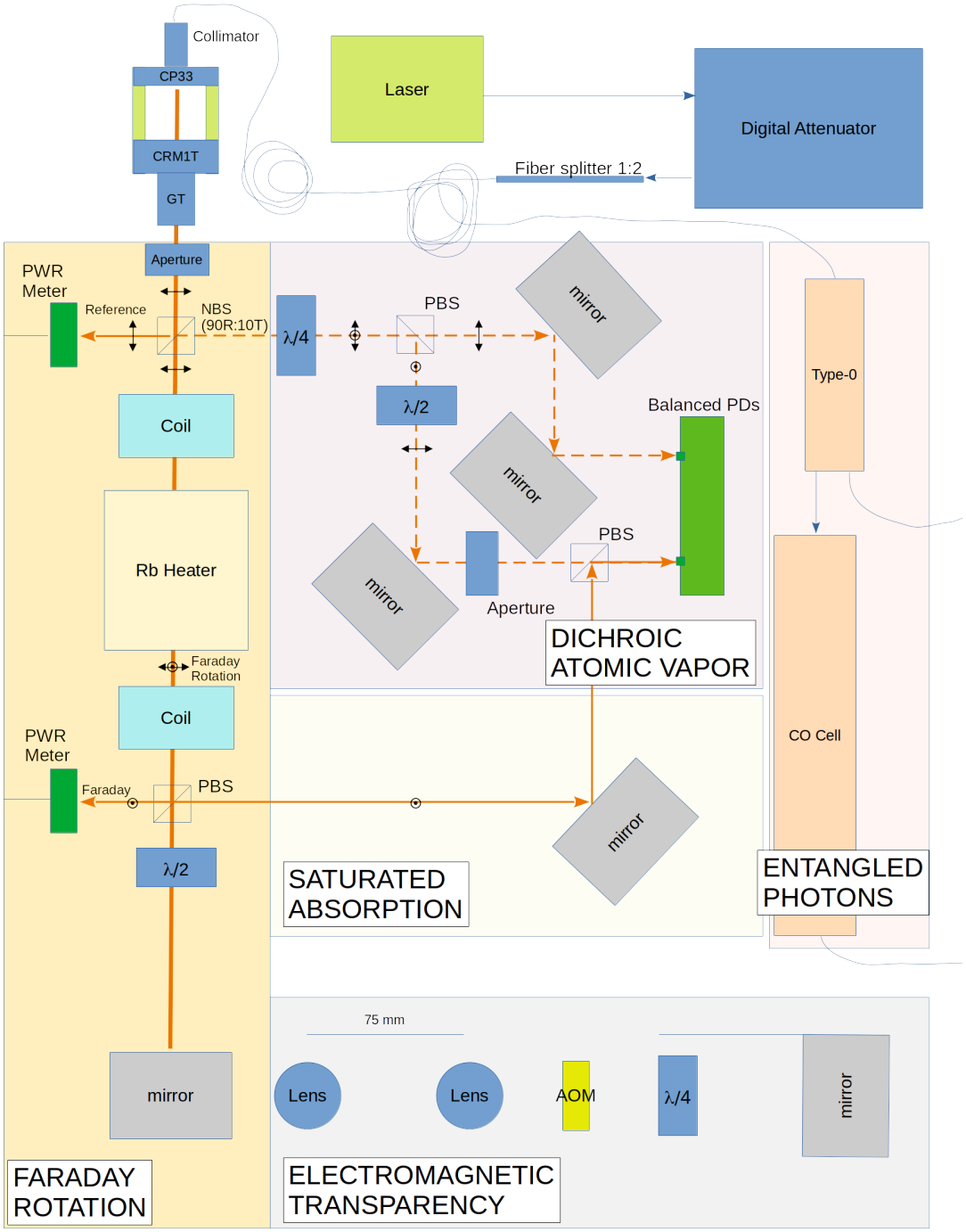

Figure 1. Optics components and relevant experiments for Applied Quantum Mechanics course (COSC 315).

Detailed below are the components and costs associated with various experiments for the Applied Quantum Technology lab series. These costs are summarized in Table 1, but are broken out further below.

Table 1. Totals of different quantum experiments.

Quantum Experiment Category	**Cost**
Laser Components	$9,833.23
Data Acquisition and Opto-mechanics	$10,331.65
Faraday Rotation	$7,004.11
Spectroscopy (SAS and DAVS)	$4,726.24
Electromagnetic Induced Transparency	$15,476.17
Hyper-entangled photons (home-built option)	$77,474.34 ($47,000)
TOTAL	**$124,845 ($94,371)**

The 18"x24" aluminum optics table and laser tuned for 780.2 nm to target the Rb-85 D2 spectroscopic line (and light attenuation components), totals **$9,833.23** (including 6% Md tax), as shown in Table 2.

Table 2. Laser components for quantum sensing experiments.

System & Parts	**Vendor**	**Model**	**Price**	**QTY**	**Total**
Aluminum Breadboard, 18 x 24" x 1/2", 1/4"-20 Taps	Thorlabs	MB1824	$459.34	1	$486.90
			SUBTOTAL		**$486.90**
Laser	Eblana Photonics	EP780-2-DM-DX1-FM	$6,210.00	1	$6,582.60
Digital Variable Optical Attenuator	Thorlabs	DV800PA	$1,926.00	1	$2,041.56
1x2 PM Fiber splitter 50-50 780nm	Thorlabs	PN780R5A1	$681.29	1	$722.17
			SUBTOTAL		**$9,346.33**

Other components needed in general for these experiments are detailed in Table 3, totaling **$10,331.65** (including 6% Md tax). These components include data acquisition, opto-mechanics, and basic laser and magnetic field diagnostics.

Table 3. Other components needed for the underlying quantum experiment infrastructure.

System & Parts	**Vendor**	**Model**	**Price**	**QTY**	**Total**
Data Acquisition					
Oscilloscope or Digitizer					
4 CH Digitizer, 1.5 Gsa/s, 500 MHz BW, 16 Digital CH	PicoTechnology	PicoScope 3418E MSO	$5,475.00	1	$5,803.50
PC Laptop			$800.00	1	$848.00
USB Hub			$100.00	1	$106.00
			SUBTOTAL		**$6,757.50**
Accessories					
Hall probe	Digikey	TP002	$485.00	1	$514.10
NIR Detector Card, 700 - 1400 nm	Thorlabs	VRC7	$128.10	2	$271.57
Laser safety goggles, OD > 5 780 nm, OD>1.5 for 1110	Edmund Optics	12-728 12-711	$280.00	2	$593.60
CMOS Camera	Thorlabs	CS165MU	$479.86	1	$508.65
			SUBTOTAL		**$1,887.92**
Posts and Spacers					
Ø1" Double Pedestal Base Adapter, 8-32 and 1/4"-20, Length = 1"	Thorlabs	SBE2	$31.57	24	$803.14
Compact Clamping Fork for Ø1"	Thorlabs	SCF1	$29.43	24	$748.70
Ø25.0 mm Post Spacer, Thickness = 10 mm	Thorlabs	RS10M	$10.75	5	$56.98
Ø25.0 mm Post Spacer, Thickness = 1 mm	Thorlabs	RS1M	$8.20	2	$17.38
Ø25.0 mm Post Spacer, Thickness = 2 mm	Thorlabs	RS2M	$8.51	2	$18.04
Ø25.0 mm Post Spacer, Thickness = 5 mm	Thorlabs	RS5M	$9.60	2	$20.35
Ø25.0 mm Post Spacer, Thickness = 7 mm	Thorlabs	RS7M	$10.11	1	$10.72
Ø25.0 mm Post Spacer, Thickness = 8 mm	Thorlabs	RS8M	$10.30	1	$10.92
			SUBTOTAL		**$1,686.23**

A primary experiment for students to understand is the concept of Faraday rotation. With Faraday rotation, the angle of the laser beam's polarization rotates when an alkali gas (i.e. rubidium) is exposed to an applied magnetic field. By measuring the angle of this rotation, the applied magnetic field can be calculated. Hence, the quantum concept of Faraday rotation can be used to create a

quantum magnetometer. The setup for this Faraday rotation experiment is shown on the left side of Fig. 1. As shown in Table 4, the optical components and cost totals **$7,004.11** (including 6% Md tax).

Table 4. Faraday rotation components

System & Parts	Vendor	Model		Price	QTY	Total
Free-Space Collimation & Polarization						
fiber collimator	Thorlabs	F220APC-780		$262.43	1	$278.18
SM1-Threaded Adapter	Thorlabs	AD11F		$36.22	1	$38.39
Cage Plate	Thorlabs	CP33		$20.43	1	$21.66
Cage Assembly Rod, 1.5" Long	Thorlabs	ER2-P4		$26.82	1	$28.43
Cage Rotation Mount	Thorlabs	CRM1T		$102.65	1	$108.81
30 mm Cage Mounting Bracket with 8-32 Captive Screw	Thorlabs	CP33C		$26.19	1	$27.76
SM1 Lens Tube Mount	Thorlabs	SM05PM5		$61.34	1	$65.02
Unmounted Glan-Laser Polarizer	Thorlabs	GL5-B		$836.37	1	$886.55
SM1 Retaining Ring	Thorlabs	SM1RR		$5.21	1	$5.52
Adapter with External SM1 Threads	Thorlabs	SM1A6		$24.42	1	$25.89
SM1-Threaded Manual Beam Shutter	Thorlabs	SM1SH1		$71.82	1	$76.13
				SUBTOTAL		**$1,562.33**
Probe Beam Sampler						
90:10 (R:T) Non-Polarizing Beamsplitter Cube, 700 - 1100 nm, 1/2"	Thorlabs	BS074		$227.52	1	$241.17
Platform Mount for 1/2" Beamsplitter	Thorlabs	BSH05		$56.08	1	$59.44
				SUBTOTAL		**$300.62**
Vapor Cell						
Heater Assembly	Thorlabs	GCH25-75		$1,079.15	1	$1,143.90
Rubidium Borosilicate Reference Cell	Thorlabs	GC25075-RB		$615.39	1	$652.31
Heater and TEC Temperature Controller	Thorlabs	TC300B		$1,134.51	1	$1,202.58
30 mm Cage Mounting Bracket with 8-32 Captive Screw	Thorlabs	CP33C		$26.19	1	$27.76
Ø1.25" Studded Pedestal Base Adapter	Thorlabs	BE1		$11.59	1	$12.29
Cage Assembly Rod, 1/2" Long	Thorlabs	ER05-P4		$5.99	1	$6.35
				SUBTOTAL		**$3,045.19**
Electromagnet						
Adjustable Power Supply with 2.1mm / 5.5mm DC - 3V to 12V at 5A	Adafruit		4880	$17.50		$0.00
FNIRSI DPS-150 Plus DC Power Supply Variable	FNIRSI	DPS-150 Plus		$98.99		$0.00
DC Power Supply Variable, 0-32V 0-10A Switching Bench Power Supply	Jesverty	SPS-3010V		$48.39	1	$51.29
Magnetic induction coil	Walmart	Raindrops		$4.02		$0.00
Coil 550/600 Turns	Arbor Scientific	98-6505		$32.50	2	$68.90
				SUBTOTAL		**$120.19**
Faraday Split						
1/2" Polarizing Beamsplitter Cube, 620 - 1000 nm		PBS122		$242.77	1	$257.34
Platform Mount for 1/2" Beamsplitter	Thorlabs	BSH05		$56.08	1	$59.44
				SUBTOTAL		**$316.78**
Reflect Light						
25.4mm Dia. NIR, Precision Broadband Laser Mirror	Edmund Optics	45-597		$170.66	1	$180.90
Kinematic Mirror Mount for Ø1" Optics Post-Centered	Thorlabs	KM100CP		$89.61	1	$94.99
				SUBTOTAL		**$275.89**

Using most of the same components from the Faraday rotation/magnetometer setup, we can also conduct Saturated Absorption Spectroscopy (SAS) and Dichroic Atomic Vapor Spectroscopy (DAVS), as also shown in Fig. 1. The extra cost to add these optical components is **$4,726.24** (including 6% Md tax), as shown in Table 5.

Table 5. Additional components needed to conduct SAS and DAVS quantum experiments.

System & Parts	Vendor	Model	Price	QTY	Total
Polarization Control					
Ø1/2" Zero-Order Half-Wave Plate, Ø1" Mount, 780 nm	Thorlabs	WPH05M-780	$542.76	1	$575.33
Ø1/2" Zero-Order Quarter-Wave Plate, Ø1" Mount, 780 nm	Thorlabs	WPQ05M-780	$542.76	1	$575.33
Rotation Mount for Ø1" (25.4 mm) Optics	Thorlabs	LRM1	$109.65	2	$232.46
			SUBTOTAL		**$1,383.11**
Power Meters					
Power detector free space, 400 - 1100 nm, 1 nW - 20 mW	Thorlabs	S120C	$381.34	2	$808.44
Power Meter Interface with USB, RS232, UART, Analog Out	Thorlabs	PM101	$568.63	2	$1,205.50
			SUBTOTAL		**$2,013.94**
Balanced PD					
Free-Space Balanced Photodetector, Si	Thorlabs	PDB210A	$1,253.95	1	$1,329.19
			SUBTOTAL		**$1,329.19**

An amazing quantum effect is known as Electromagnetic Induced Transparency (EIT), also known as Coherent Population Trapping (CPT). When a pump laser traverses an alkali gas (i.e. rubidium), and then a frequency-shifted reflected beam passes back through the gas at the resonance frequency of the Zeeman-shifted hyperfine ground states of Rb, the gas stops absorbing (hence,

"transparency"). This induced transparency can be used as a more precise magnetometer than Faraday rotation, because the applied magnetic field causes a very narrow resonance for EIT to occur, and therefore a very precise magnetometer by adjusting the frequency of the reflected "probe" beam. The additional "frequency shifter" components needed for this set of experiments are shown at the bottom of Fig. 4. The cost for the frequency shifter is **$15,476.17** (including 6% Md tax), as detailed in Table 6.

Table 6. Components for a frequency shifter that will allow for EIT experiments and a more precise magnetometer experiments.

System & Parts	Vendor	Model	Price	QTY	Total
Frequency Shift					
AOM 1.6 GHz	Brimrose	TEF-1500-100-780	$7,935.00	1	$8,411.10
RF power	Brimrose	FF-1500-B2-F1	$5,463.00	1	$5,790.78
RF cable	Brimrose	RF-SMA-SMA-1M	$95.00	1	$100.70
Best Form Lens, Ø1", f = 100.0 mm, AR Coating: 650 - 1050 nm	Thorlabs	LBF41100-B	$203.30	1	$215.50
Spacer, 2" x 3", 0.50" Thick	Thorlabs	BA2S6	$34.96	1	$37.06
Spacer, 2" x 3", 0.15" Thick	Thorlabs	BA2S4/M	$28.11	2	$59.59
Lens Mount with Retaining Ring for Ø1" Optics, 8-32 Tap	Thorlabs	LMR1	$17.62	1	$18.68
Plano-Concave Lens, Ø1/2", f = -25.0 mm, AR Coating: 650-1050 nm	Thorlabs	LC1054-B	$36.64	1	$38.84
Lens Mount with Retaining Ring for Ø1/2" Optics	Thorlabs	LMR05	$18.18	1	$19.27
25.4mm Dia. NIR, Precision Broadband Laser Mirror	Edmund Optics	45-597	$170.66	1	$180.90
Kinematic Mirror Mount for Ø1" Optics Post-Centered	Thorlabs	KM100CP	$89.61	1	$94.99
Best Form Lens, Ø1", f = 75.0 mm, AR Coating: 650 - 1050 nm	Thorlabs	LBF41075-B	$203.30	1	$215.50
Lens Mount with Retaining Ring for Ø1" Optics, 8-32 Tap	Thorlabs	LMR1	$17.62	1	$18.68
Spherical concave mirror, effective focal length 76.2mm	Edmund Optics	73-002	$159.00	1	$168.54
Lens Mount with Retaining Ring for Ø1" Optics, 8-32 Tap	Thorlabs	LMR1	$17.62	1	$18.68
Mounted Zero-Aperture Iris, Ø12.0 mm Max Aperture, TR3 Post	Thorlabs	ID12Z	$82.43	1	$87.38
			SUBTOTAL		**$15,476.17**

A very important concept for quantum technology going forward is the quantum entanglement. Two photons can be created that are entangled, either by polarization (horizontal and vertical polarizations) or time-energy (two different wavelength photons generated at same time). Multiple important quantum technology experiments can be developed for entangled photons, including ghost spectroscopy and entangled Quantum Key Distribution. However, the hardware needed for infrared photons can be expensive.

The added components to generate hyper-entangled photons (polarization and wavelength) are shown on the right side of Fig. 1. The cost for these additional components is **$77,474.34** (including 6% Md tax), as detailed in Table 7. Please note that two Avalanche Photo-Diodes (APDs) operating in the infrared (IR) are needed for these experiments. Unfortunately, there are only a few vendors who make turn-key IR APDs, and the cost is about $20,000 each. However, the actual IR APD sensor is only $450. Often universities will make their own electronics for the APD sensors at much lower cost than these turn-key vendors. As such, we believe we could reduce the total cost for hyper-entangled photons by about $30,000 if build the electronics ourselves (grand total of about **$47,000**).

Entangled photons are a very important quantum tool being used by industry, so we believe this entangled photon source should be pursued. Additionally, our entangled photons will be in the important Super-C (1510 nm -1560 nm) and Super-L (1560 nm - 1610 nm) wavelengths, which are used by the telecommunications industry. Students competent at using entangled photons in the C- and L- bands is very important for the quantum industry and future quantum technology research.

Table 7. Components and costs to generate hyper-entangled photons and their detection.

System & Parts	Vendor	Model	Price	QTY	Total
Entangled Photon Ghost Spectroscopy					
Fiber-coupled waveguide entangled photons Type-0	Covesion	WGCO-1560	$11,354.00	1	$12,035.24
Temperature controller	Covesion	OC3	$1,514.00	1	$1,604.84
45 deg Faraday rotator	Ozoptcs	FOR-11P-780-5/125-P-P-40-SCA-3-1	$500.00	1	$530.00
1x2 780 nm/1560 nm SM Filter WDM (1550 +/- 40 nm)	WDMQuest	W9900-S	$195.00	1	$206.70
Electrically Controlled 1x2 Compact Fiber Switch-1550 nm	WDMQuest	Q1000-S	$160.00	1	$169.60
2x2 PM Coupler, 780 ± 15 nm, 50:50 Split, ≥18 dB PER, FC/APC	Thorlabs	PN780R5A2	$681.29	0	$0.00
Acetylene CO reference cell pigtailed FC/APC	Wavelength References	C2H2-12-H(3)-200-FCAPC	$1,250.00	1	$1,325.00
Digital Tunable Bandpass Filter, 1527 - 1567 nm	Thorlabs	TOF1550	$5,136.00	1	$5,444.16
APD Geiger mode			$20,000.00	2	$42,400.00
Timetagger	quTools	QuTag-LC	$7,000.00	1	$7,420.00
Optical channel performance monitor	Bayspec	OCPM-100-080-1510-FA	$5,980.00	1	$6,338.80
			SUBTOTAL		**$77,474.34**