MICROWAVE ACTIVE MEDIA STUDIES FOR PASER

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Abstract

Particle Acceleration by Stimulated Emission of Radiation (PASER) is method of particle acceleration in which a beam gains energy from an active medium through stimulated emission. To obtain the required stimulated emission for the PASER effect the particle beam intensity is modulated at the frequency corresponding to the energy difference between the levels in which population inversion is achieved in the active medium. We propose to use solid-state active medium based on the Zeeman effect (triplet systems) for the PASER. Modulation of the beam at the frequency of the transition to obtain stimulated emission can be produced by means of a deflecting cavity. A transverse "beamlet" pattern will be produced on the AWA photocathode gun by using a laser mask. The transverse beam distribution will be transformed into a longitudinal beam modulation as the beam passes through the deflecting cavity. Two designs are being considered: X-band and a 100 GHz designs. The high frequency design yields a higher total energy gain but requires Tesla-level magnetic fields.

In this paper we report on the development of active media and RF bench tests of active media loaded structures.

INTRODUCTION

The ability of electron to gain energy from active medium was discussed in [1] as an inverse process to Frank-Hertz [2] experiment. The free electron absorbs a photon emitted by a bound electron when the latter drops from an excited state to the ground state. For this process to become useful for particle acceleration stimulated emission needs to occur [3]. Such an effect was recently demonstrated in the infrared [4]. The active medium in the experiment was a CO_2 gas mixture pumped via a plasma discharge. Stimulated emission occurs if the beam spectrum has a frequency component corresponding to the frequency of the transition, for example if there is a charge modulation of the bunch of particles injected into the active medium, with the modulation frequency corresponding to the energy of the emitted photons.

We are investigating the possibility of using a solid state active medium based on Zeeman effect [5] for PASER and MASER applications. The medium is pumped with an intense optical pulse from a laser. The energy of the emitted photons is controlled by the Zeeman magnetic field which allows some tunability. The kG-level fields that can be easily achieved correspond to ~ 10 GHz frequencies, while superconducting Tesla-level magnetic fields yield 100 GHz – THz frequencies.

In this paper we present results of the active microwave medium development process and electron paramagnetic resonance measurements of the active medium. Results of the first generation RF bench test will also be presented. We will also present a method to produce a modulated electron beam for future PASER experiments.

DEVELOPMENT AND ELECTRON PARAMAGNETIC RESONANCE MEASUREMENTS OF ACTIVE MEDIUM

The simplest energy level structure based on the Zeeman Effect is the triplet. We tested various chemicals dissolved in different solvents [6]. The goal of the study was to find the combination that gives the highest emission signal. A derivative of C_{60} (fullerene or buckyball), PCBM (phenyl-C_{61}-butyric acid methyl ester) was picked for further study (Figure 1).

The analysis of the triplet is done by electron paramagnetic resonance (EPR) spectroscopy. Typically EPR measurements are made with a constant frequency X-band microwave source, and the spectrum is actually obtained by sweeping the applied magnetic field (H~3kG for λ~3 cm). The maser transition frequency can thus be adjusted by changing the magnetic field.

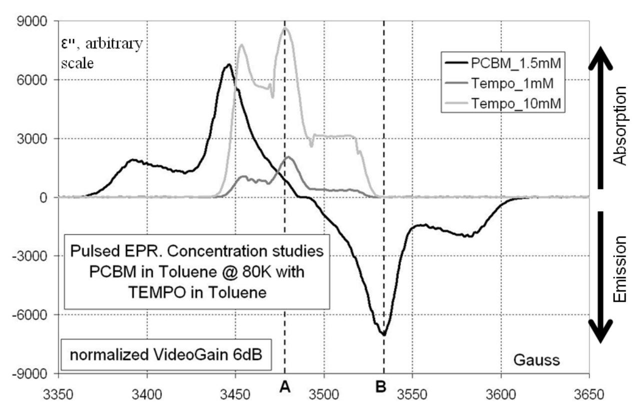

Figure 1: EPR measurements of TEMPO and PCBM at temperature of 80K and optimal concentration (~1mM).

The PCBM signal is compared to the absorption line of a reference compound TEMPO (2,2,6,6–Tetramethylpi-peridine-1-oxyl) at two different concentrations. There are several aspects that determine the strength of an EPR signal (population inversion). There is no known recipe to maximize the triplet signal. Many factors contribute to the signal level, such as lifetime of the excited state, concentration, temperature effects, solvent properties and

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other properties. We keep working towards improving the population inversion in triplet system. One particular interesting direction is our development of solid samples, utilizing a polymer as a solvent for PCBM.

EPR spectroscopy is a very sensitive technique. It relies on relative changes in the properties of a resonator partially loaded with the active medium. We designed an experiment for direct RF measurement of the active medium.

RF BENCH TEST OF ACTIVE MEDIUM

We manufactured a tunable TE_{011}-mode based resonator. The TE_{011} mode was chosen to provide an appropriate field pattern with the magnetic energy density in the middle of the cavity, where the sample is placed. This configuration minimizes the effects of dielectric losses in the sample. The high quality factor allowed us to perform an EPR-type measurement first, before moving on to Q-factor manipulation experiments. The TE_{011} mode is degenerate with the TM_{111} mode. We machined a groove at the base of a cylinder to remove the degeneracy. RF is coupled into the cavity via a loop on the sidewall. The Q-factor of the empty cavity is ~ 10000.

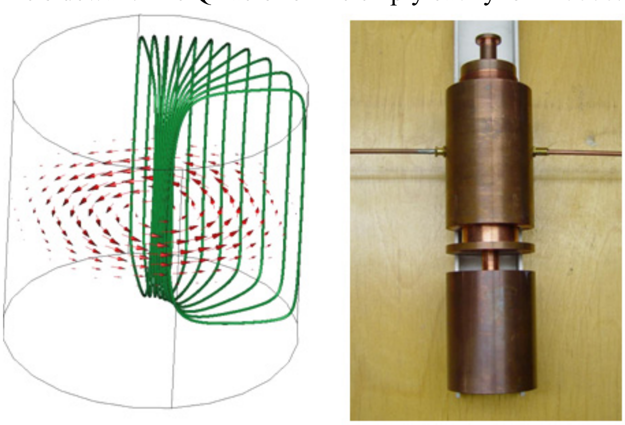

Figure 2: TE_{011} resonator fields: arrows – electric field, green – magnetic field lines. Photo of partially disassembled resonator showing tuning sections and RF connections.

The light was provided by a green 532 nm laser that could produce about 3mJ per pulse at 10 Hz. We used an optical fiber to deliver the light to the sample.

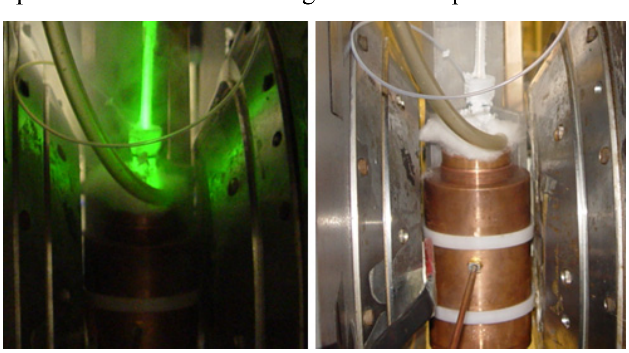

Figure 3: EPR tube is inserted in a resonator. An optical fiber is inserted in the EPR tube. It delivers 3mJ of green light to the sample inside the EPR tube. Also on a picture: RF coupled in by a loop. On the bottom of a resonator is a dewar fixture to blow 120K cooled nitrogen through the cavity.

Network Analyzer Measurement of TEMPO

The EPR reference chemical, TEMPO, does not need cooling or optical excitation. We were able to measure its response with a network analyzer. We are interested in the change of coupling and quality factor. The measured reflection curve is presented below in Fig.4.

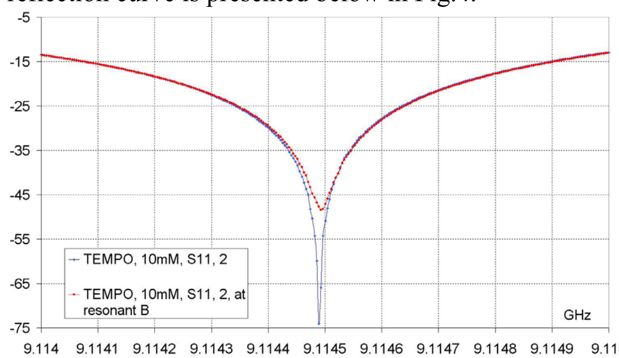

Figure 4: Network analyzer measurement of solid TEMPO (10mM). S_{11} (reflection) at resonant magnetic field ($h \bullet \nu = g_e \mu_b B_0$), (red) and 100 gauss off-resonance (blue).

The difference between the Q-factor in the case of a resonant magnetic field ($h \cdot \nu = g_e \mu_b B_0$) and 100 Gauss off –resonance was measured to be 1.2%. It is important to add that the difference in impedance at the resonance (coupling) is higher than the difference in Q-factor (~ 2%). This was measured via Smith Chart on the network analyzer for S_{11} measurements. It is a large difference considering that the sample volume is about 0.5% of the cavity volume.

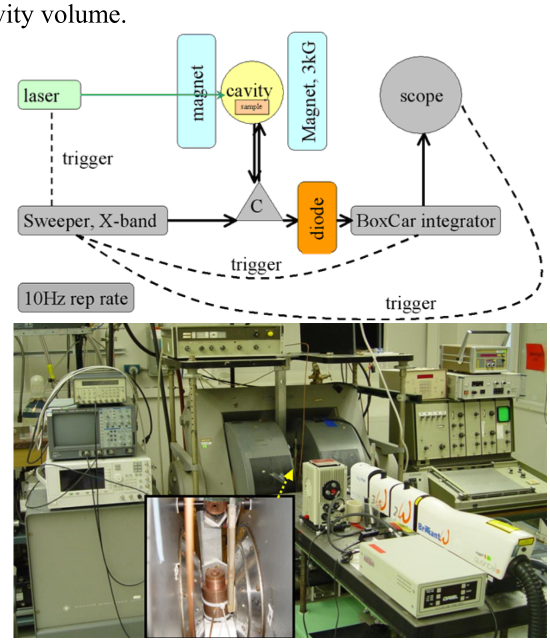

Figure 5: RF measurement system.

Solid (not diluted) TEMPO yielded a 20% quality factor change and almost 40% change in coupling. This effect can be used for tunable RF absorption.

RF Measurement of Active Medium

The PCBM sample required cooling and light delivery. Sample cooling was done using a tube dewar and cold nitrogen (~120 K) was blown through the tube dewar.

The RF measurement was similar to a network analyzer measurement of the S_{11} (reflection). The RF signal from a sweeper goes through the circulator into the resonator. Reflection goes through the circulator to a diode and then is integrated by a boxcar unit. The whole sequence is triggered in such a way, that the integration happens after the laser pulse. The resulting signal is viewed on the scope. As a result each point on the reflection curve (Figure 6) corresponds to a separate laser pulse.

EPR data (Figure 1) suggest that at temperature of 80K emission from PCBM is comparable to absorption of a 10mM TEMPO. However, in our experiment we observed only a small relative change in coupling for the PCBM sample. Our cooling system was capable of only maintaining a temperature of 120K reliably. On the red curve we can see the moment the laser was turned on.

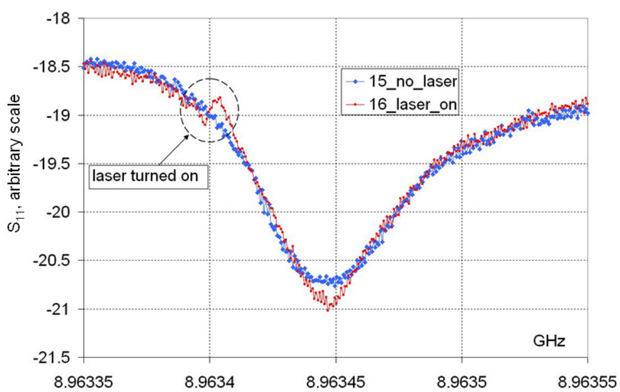

Figure 6: RF measurement of PCBM, 1mM. Magnetic field is at resonance, emission. Red points – laser on, blue points – laser off. We zoomed in on the resonance and observed a small change in coupling.

The next generation RF measurement will employ a variable flow cryostat with a different type of resonator.

BUNCH TRAIN GENERATION

The PASER experiment will require a modulated beam or a bunch train. Several methods of bunch train generation have been studied at the AWA (Argonne Wakefield Accelerator facility). One idea relies on temporal laser pulse shaping for a photocathode gun [7]. Another one makes use of transverse-to-longitudinal emittance exchange beamline [8].

SUMMARY

We have identified PCBM, a fullerene derivative, as a candidate active media for future microwave PASER and low-noise amplifier experiments. A first generation RF test was performed with Zeeman effect – based active medium. Despite being limited by cooling system capability we observed a change in coupling. The second generation experiment is being designed with a variable flow cryostat.

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