X-BAND PASER EXPERIMENT*

A. Kanareykin#, P. Schoessow, Euclid TechLabs, LLC, Solon, OH, 44139, U.S.A.
S. Antipov, Argonne National Laboratory, Argonne, IL, 60439, U.S.A.
Levi Schächter, Technion, Haifa, Israel.

Abstract

The PASER concept for particle acceleration entails the direct transfer of energy from an active medium to a charged particle beam. The PASER was originally formulated for optical (laser) media; we are pursuing a PASER demonstration experiment based on an optically pumped paramagnetic medium active in the X-band.

We report on the development of a relatively high energy density microwave active medium consisting of a fullerene (C_{60}) derivative in a toluene solution. We discuss both the bench test of an amplifier and a beam acceleration experiment under construction that employ this medium as a power source. Applications of the technology to accelerators and microwave components will be presented.

ACTIVE MICROWAVE MATERIALS

The principal goal of this project is the development and demonstration of a PASER (Particle Acceleration by Stimulated Emission of Radiation) operating in the microwave regime. This accelerator is based on an active medium where the optical energy from an intense light source is transferred into the kinetic energy of an accelerated electron beam [1]. Recently discovered chemical systems such as fullerene molecules dissolved in organic solvents [2] have been demonstrated to be active microwave amplifying or absorbing materials. The feasibility of a practical PASER-based accelerator could be greatly advanced by the solid state active media accelerating concepts we are developing.

This work relies heavily on both CW and time-resolved EPR (electron paramagnetic resonance, also known as ESR, electron spin resonance) measurements of candidate materials. The system is shown schematically in Figure 1 for the materials we are investigating.

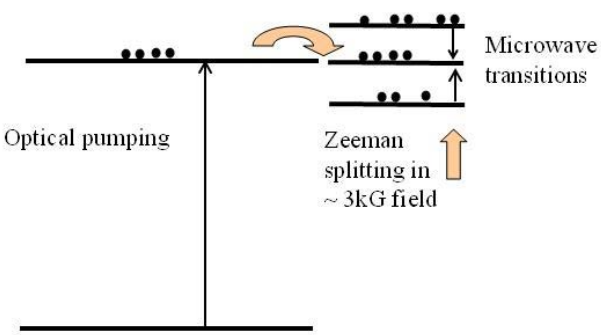

Figure 1: Zeeman effect in optical pumping of active microwave material. Arrows indicate emissive and absorptive transitions.

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alexkan@euclidtechlabs.com

The active material is located in a uniform magnetic field. The material is pumped using a flash lamp or laser pulse. The energy level corresponding to the optical transition is split via the Zeeman Effect and as shown produces a population inversion. There are two possible transitions to the ground state corresponding to the double peaked EPR spectra seen in our experiments.

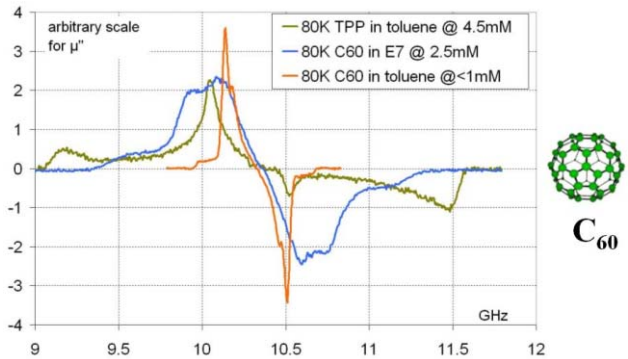

Figure 2: EPR measurements of various triplet systems.

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~3000 Oe for λ~3 cm). The maser transition frequency can thus be adjusted by changing the magnetic field.)

The simplest energy level structure based on Zeeman Effect is the triplet (Figure 1). We tested various chemicals dissolved in different solvents. The goal of the study was to find the combination that gives the highest emission signal. **C_{60}** (fullerene or buckyball) was picked for further study (Figure 2).

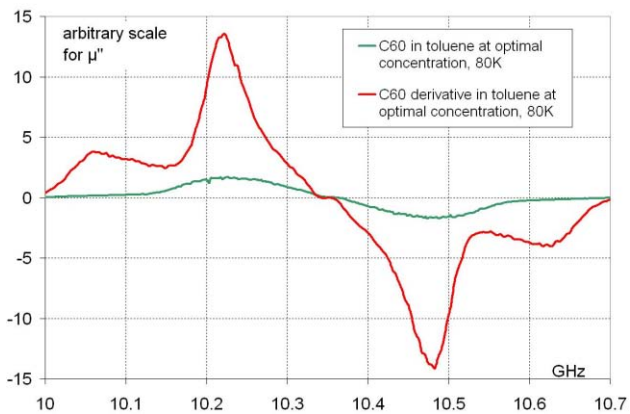

Figure 3: Comparison of C_{60} signal with a signal from the C_{60} derivative. Solvent is the same in both cases – toluene.

A typical EPR signal can be interpreted as being proportional to the imaginary part of the permeability. The triplet signal has an absorption (positive μ") line

followed by an emission line (negative μ") with some shape variations.

There are several aspects that determine the strength of a signal (population inversion). There is no known recipe how to maximize the triplet signal. Many factors contribute to the signal level, such as lifetime of the excited state and other properties. Temperature, concentration, solvent type and other effects will be discussed further. By trial and error we have identified a particular fullerene derivative that produces a significantly higher signal (Figure 3).

The lifetime of the triplet state depends on the temperature. This quantity can also be measured by the EPR technique. It is called the DAF (delay after flash) time (Figure 4).

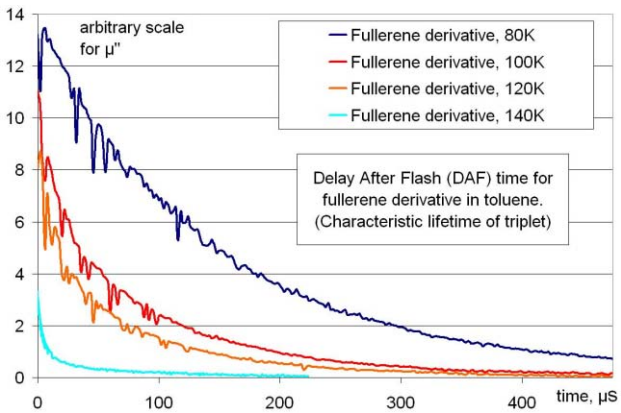

Figure 4: Triplet lifetime as a function of temperature.

CONCENTRATION AND TEMPERATURE EFFECTS

High concentrations of the active component provide more spins and thus more energy can be stored in the medium. However the solution becomes less transparent to the pump signal. This can lead to non-uniform media illumination by the pump and thus a weaker signal. More significantly, there is a greater interaction between excited molecules as the concentration increases. This results in loss of the population inversion (and reduction of the maximum amplitude of the signal) known as quenching. Therefore the concentration has to be kept small (Figure 5).

Some temperature effects can be seen in figure 4. At higher temperatures there is a greater interaction between excited molecules that also results in loss of the population inversion and is also a quenching effect (Fig,6).

One method under investigation to compensate for quenching is to restrict the molecular motion in a *solid solvent*. We have manufactured several solid samples and found a matrix that produces results comparable to liquid solvent at low temperature. At higher temperatures it outperforms a liquid sample. Using the solid material we were able to measure a triplet signal even at room temperature (Figure 6).

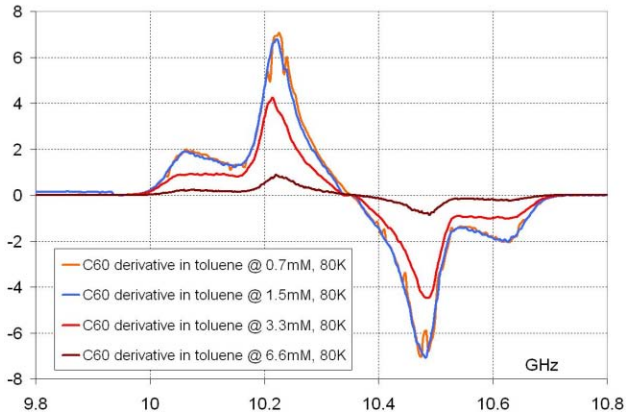

Figure 5: EPR signal dependence on concentration.

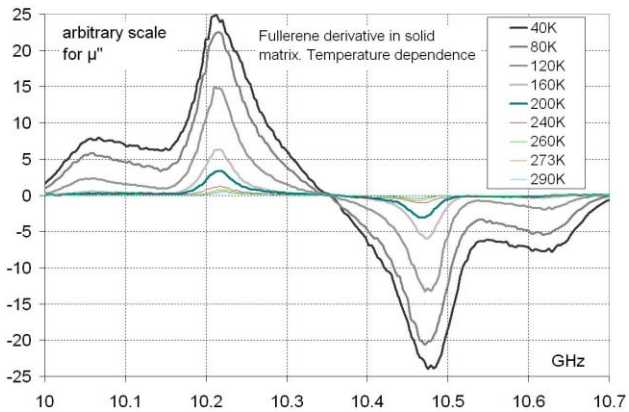

Figure 6: EPR signal dependence on temperature.

Q-FACTOR IN ACTIVE STRUCTURES

The paramagnetic active media considered here couple their energy to the magnetic field of a charged particle or EM wave. Therefore an active medium can be characterized by a negative imaginary part of μ". We find it convenient to describe the medium by its “activity tangent”, defined analogously to the loss tangent in dielectrics.

EPR data can be converted to μ" using a reference sample. We used TEMPO, a standard calibration material in EPR spectroscopy, as a reference. The highest experimental values we achieved so far correspond to an activity tangent of $1.5 \cdot 10^{-4}$. Paramagnetic activity is comparable to dielectric loss in the solvent.

We are working on further improvement of the active media from the chemistry perspective. Also we are trying to improve the situation by cavity design.

The quality factor of a resonator, Q, is determined by the stored EM energy, loss in the cavity walls, dielectric losses and in the case of active media-based device, by its magnetic activity (negative losses). In the case when the

activity almost compensates the losses one can obtain extremely high quality factors (1).

$$Q = \frac{\omega \cdot U_{stored}}{P_{wall\_loss} + P_{diel\_loss} - P_{magnetic\_activity}} \qquad (1)$$

We simulated an example of a TM_{011} mode based cylindrical cavity. Figure 7 presents the Q-factor dependence on the activity tangent value. This example shows that once the activity tangent of an active media becomes comparable to the dielectric loss tangent of the host media one can obtain extremely high Q factors. When magnetic activity compensates the losses Q factor becomes negative. This corresponds to emission of microwaves from the medium.

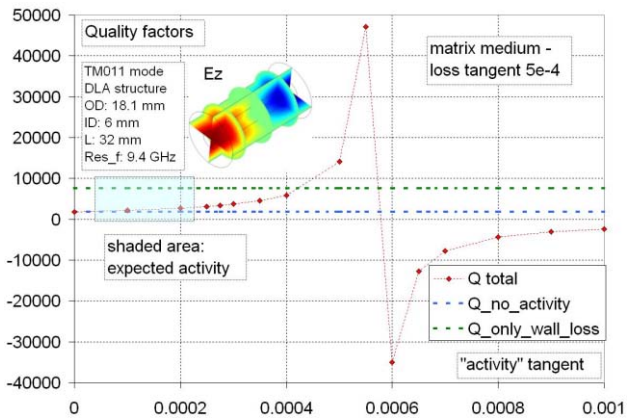

Figure 7: Quality factor dependence on concentration.

The minimum activity tangent that is required for emission can be lowered via cavity design. The energy density of the resonant mode due primarily to the electric field has to be located in a low dielectric loss material, while the magnetic energy density has to be concentrated in a region of the cavity containing the active medium.

AMPLIFIER AND BEAM EXPERIMENTS

Bench tests are underway to measure maser amplification in a bulk quantity of fullerene based active materials. In order to minimize losses we plan to use a cylindrical TE cavity loaded with a smaller cylinder of active medium on axis to minimize the losses in the medium caused by the electric field.

Based on the results so far we have begun designing a beam acceleration experiment [3]. The EPR dipole (Fig.8) at the ANL 3 MeV van de Graaf is available for the experiment and will allow us to use a large volume of active material without the expense of constructing a new magnet. The dipole was designed for electron radiolysis experiments and so has beam entrance and exit ports machined into the pole pieces along the magnetic axis. It will not be initially feasible to move the dipole to the Argonne Wakefield Accelerator linac as originally planned; instead we will perform the acceleration tests using the beam from the van de Graaf.

The beam test apparatus is positioned between the magnet poles. An elliptical optical cavity is machined from a block of aluminum, with the interior surface receiving a mirror polish. The test device and flash lamp are located at the foci. Only the active medium needs to be immersed in the magnetic field: this provides more design flexibility than the solenoid originally intended for this experiment..

CONCLUSIONS

We studied various triplet systems in a search for active media. The highest reported EPR signals were improved by order of magnitude. We also studied concentration optimization as well as temperature effects.

Current levels of activity are comparable to the dielectric losses in the host media. This is currently the major limitation for practical devices. We are investigating ways to overcome the losses by RF design of test cavities and improvement of the active media chemistry.

A solid sample of the medium was tested and was found to improve the temperature dependence of the activity. Room temperature activity was achieved. Using active media dissolved in a solid matrix exhibits a signal at high temperatures and is also expected to be able to support higher concentrations of the fullerene component without quenching effects. Uniform solid samples are more difficult to manufacture, but easier to handle than a liquid. We are in the process of developing improved techniques for making solid active media.

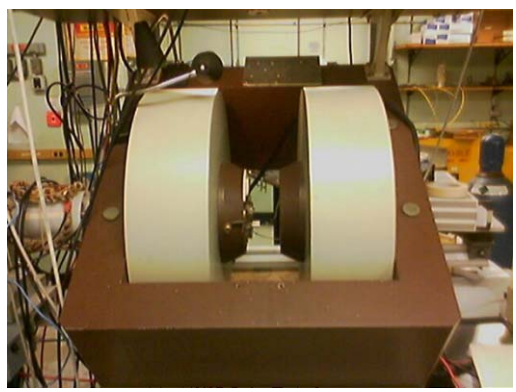

Figure 8: EPR dipole in beamline at the ANL 3MeV van de Graaf.

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