STATUS OF THE MICROWAVE PASER EXPERIMENT*

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Abstract

The PASER is a new method for particle acceleration, in which energy from an active medium is transferred to a charged particle beam. The effect is similar to the action of a maser or laser with the stimulated emission of radiation being produced by the virtual photons in the electromagnetic field of the beam. We are developing a demonstration PASER device operating at X-band, based on the availability of a new class of active materials that exhibit photoinduced electron spin polarization. We will report on the status of active material development and measurements, numerical simulations, and preparations for microwave PASER experiments at the Argonne Wakefield Accelerator facility.

INTRODUCTION

The principal goal of this project is the development and demonstration of the PASER (*P*article *A*cceleration by *S*timulated *E*mission of *R*adiation) operating in the microwave regime. This accelerator is based on an active medium - a new concept where the optical energy from an intense light source is transferred into the kinetic energy of an accelerated electron beam. Recently discovered chemical systems such as Tetraphenylporhpyrin (TPhP) or fullerene (C_{60}) molecules dissolved in organic solvents have been demonstrated to be active microwave amplifying or absorbing materials [1].

The main objective of the project is to perform proof-of-principle experiments to demonstrate the feasibility of the microwave PASER. In outline, the active paramagnetic medium is contained in a resonant cavity or waveguide placed in a static magnetic field. When pumped by an intense optical pulse, a population inversion is created in the medium. Initial bench test experiments will study the amplification of a microwave pulse by active media in bulk without the need for an EPR spectrometer. The bench test apparatus will then be modified by providing a cavity with a beam channel to accommodate an acceleration experiment.

Besides particle acceleration based on the microwave PASER, the technologies being developed under this project have a number of important potential applications. One very promising application of these materials is in their use as active amplifying substances in optically pumped low noise and relatively high operating temperature solid-state maser amplifiers. The bench test system could lead to the development of compact, portable ESR spectrometers.

This work relies heavily on both CW and time-resolved (TR) EPR (electron paramagnetic resonance, also known as ESR, electron spin resonance) measurements of candidate active materials. A review of the basic EPR principles and other background information can be found in ref. [2].

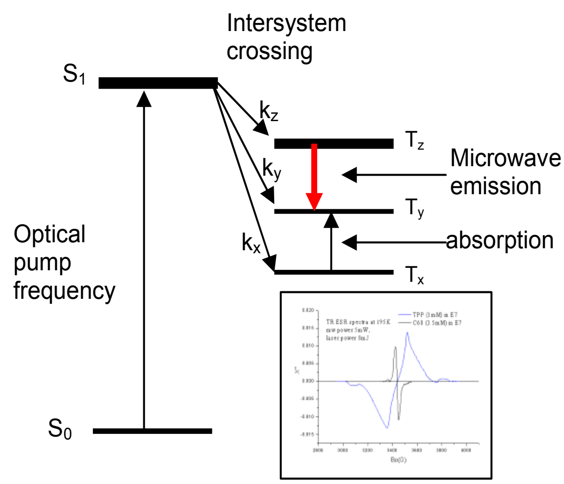

Figure 1. Energy level diagram of the active C_{60}-LC medium. Transitions to T_y can be either absorptive or emissive. Inset: EPR spectra of C_{60} (narrow curve) and TPhP showing both absorption and emission characteristics. (Negative corresponds to emission.)

ACTIVE MEDIUM DEVELOPMENT. EPR MEASUREMENTS

We have studied microwave active materials with respect to the maximum rf field amplification that can be obtained and consequently the maximum energy gain that can be demonstrated with the microwave PASER experiment. C_{60}-TPhP-E7 samples were studied with variations in the C_{60}-TPhP complex content (1:1 and 2:1 ratios) and different complex concentrations in E7 and LC2 with the purpose of selecting an optimal composition of this type of liquid crystalline solution with a maximum EPR signal over a 120-150 MHz line width. Merck E7 and LC2 (Merck ZLI-4389) liquid crystal solvents were used in these experiments.

The goal of these measurements is to find a medium with a high spin polarization density that is optimal for use in the bench test and beam acceleration experiments. This work included time resolved electron spin resonance

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(TR ESR) study of CIDEP (chemically induced dynamic electron polarization) of C_{60} and TPhP in liquid crystals.

Preliminary active media measurement results were given in [2]. Since then measurements continued using a newly developed low loss resonant sample cavity in the EPR spectrometer. A summary of the results is given in Table 1.

The ESR data is obtained as a function of the applied magnetic field for a constant rf frequency (9 GHz) over a small time interval (Fig 1 inset), and for a constant B field (corresponding to the position of a resonance) as a function of time (kinetics). The time dependence of the maximum ESR signal for TPhP-E7 is plotted in Fig. 2. The decay time constant of the signal is ~3 μs, large compared to the time required for a relativistic beam to traverse an accelerating structure.

The degree of maser amplification that can occur is roughly proportional to the size of the maximum of -χ''(ω). The relationship between the imaginary part of the susceptibility and the spin density Δn achieved in the population inversion is [3]

$$\chi'' = \frac{1}{8}[J(J+1) - M(M+1)]\hbar\gamma^2 \Delta n g(f - f_0) .$$

Assuming a J=1, M=0 transition and the line shape function $g(0) \sim 1/\sqrt{2\pi\sigma_f^2}$ where σ_f is the width of the emission peak, we can estimate Δn ~12.5x10^{17} /cm^3 for χ'' ~12.5x10^{-4}, our best measured susceptibility (see Table 1.). Assuming no losses this implies an accelerating gradient ~8 MeV/m, and demonstrates the capablility of producing a microwave PASER material interesting from an accelerator technology viewpoint.

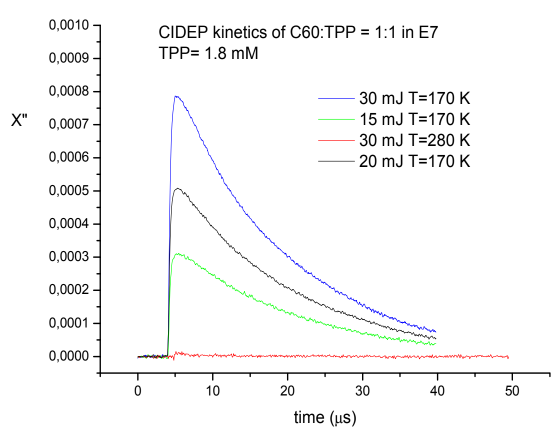

Figure 2. Measured time dependence of the negative imaginary part of the magnetic susceptibility for different pump energies. Note the difference between the 280 K and 170 K 30 mJ data.

BENCH TEST

The development of an experimental demonstration of the microwave PASER based on active paramagnetic media is challenging on a number of levels. The portions of the test structure containing the active medium must be supplied with pump energy from a flashlamp or laser and also maintained in a uniform magnetic field of about 3 kG for X-band operation.

The original literature on fullerene based active media [1] indicated that adequate performance could be obtained at relatively high temperatures ~-20 C; we have found that the required levels of performance are obtained at temperatures in the 150-195 K regime. Figure 2 shows the effect of warming the active medium to room temperature, essentially eliminating the maser effect.

We plan to cool the masing medium with liquid nitrogen; this requires a different magnet configuration than the solenoid originally planned. The bench test apparatus has undergone some modification in the light of these results on active media development and testing. The planned bench test system is now similar to one of the configurations considered for the beam test of the microwave PASER and can be easily modified to form the basis of the acceleration experiment.

Table 1. Summary of the time resolved ESR measurements of active microwave media of various compositions developed under this project. The last two rows in the table represent measurements with a new high sensitivity resonator.

[C60] (mM)	[TPhP] (mM)	Notes	$-\chi_{max}''$ (x10^{-4})	
			$\parallel B_0$	$\perp B_0$
3.525			0.81	0.81
	1.06		2.6	1.2
1.82	1.82		2.2	1.2
1.24	2.48		1.9	1.2
3.56	1.78		1.9	1.9
1.24	2.48	15 mJ pump, T=170 K	4.4	3.2
1.125	1.125	LC2	5.3	5.3
	1.0	8 mJ, T=195 K, 5 mW rf.	12.5	
3.5		8 mJ, T=195 K, 5 mW rf.	10.1	

Test Cell

The transverse dimensions of the cell are made as small as practicable to be able to obtain a uniform magnetic field over the volume of the cell with a relatively simple and compact dipole magnet. We plan to use a rectangular cavity of dimensions 1.25 cm^2 × 5 cm. The cutoff frequency for the TE_{10} mode in this waveguide when filled with the active medium (ε=2) is 8.5 GHz. Experiments will be carried out in the 9-10 GHz range; the resonant frequencies of the medium can be tuned by adjusting the magnetic field.

A window for the pump light will be located on one side of the cell. We have obtained a fine metallic mesh that has a 90% optical transmission but is essentially opaque to microwaves. A thin transparent dielectric backing layer will be used to seal the active medium in the structure.

Standard miniature microwave connectors connected to loops inside the cell represent one promising approach. The test cavity can be used as a traveling wave structure or as a resonator. The cell has a resonant mode at 8.77 GHz; by adjusting the magnetic field the amplification frequency of the medium can be set to the same frequency.

Dipole

The use of permanent magnets offers an attractive alternative to the use of electromagnets in terms of cost, compactness, and efficiency. Fields in the range we require (~3 kG) can be easily obtained using SmCo magnets. A planar geometry for the test cavity containing the medium can minimize the gap size in the magnet and improve the uniformity of the field over the cavity volume. A rectangular cross section acrylic light guide transports the pump radiation from the flashlamp to the active material. This allows considerable flexibility in the configuration of the structure and magnets.

We have designed a compact permanent magnet dipole that can produce the required magnetic field of sufficient strength and uniformity. The entire apparatus will be small enough to be immersed in the LN_2 cell available at the AWA. We expect to be able to adapt this apparatus for the beam acceleration experiment.

The dipole will be used to produce a uniform 3±0.06 kG field across the test cell. A tuning coil energized by an external DC supply will provide the required ~400 G field swing for adjusting the ESR frequency of the active medium.

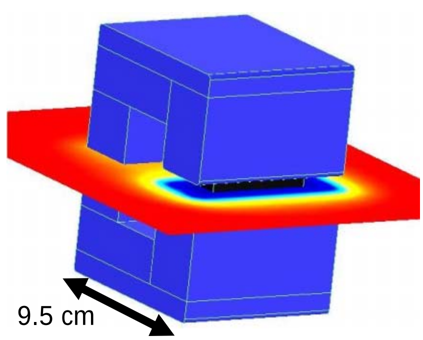

Figure 4. COMSOL 3D simulation of the compact PM dipole to be used in the bench test. The projection of the field strength on the midplane shows the uniformity of the field over the volume of the test cell (2% variation).

The design calculations were made using the Poisson/Pandira codes from LANL [4] and Comsol [5]. The field variation across the sample is less than 2% (Fig. 4). The magnet will be fabricated from soft iron and driven by a Samarium-Cobalt permanent magnet in the yoke. SmCo possesses excellent demagnetization curve characteristics [7] and is capable of operating at LN_2 temperature without degradation of performance [8].

Optical Pumping

The pump energy is generated by a Xe flashlamp; roughly 50% of the output of a Xe flash is in the 200-500 nm range [6], corresponding to wavelengths capable of driving the optical transition in the active media used in this experiment. The light is transported to the window on the test cavity via a rectangular cross section lucite light pipe. The magnet is oriented in the LN_2 bath so that the window on the cavity faces upward. The light pipe is oriented vertically and passes through the insulating cover of the LN_2 chamber so that the Xe flash and coupling optics are located outside the bath.

There are a number of commercially available flashlamp systems that are suitable for the bench test measurements. A simple optical system (e.g. a parabolic trough mirror and cylindrical converging lens) will be used to collect the light from the flash tube and couple it into the acceptance of the light guide.

Instrumentation

Design of the rf coupling to the test cavity is being performed using Microwave Studio. Two approaches are being investigated: the use of standard WG-16 or WG-17 waveguide coupled into the cell through an optimized transition section, or the use of internal loop couplers connected to standard minature microwave connectors on the cell endcaps. For both cases two ports are provided, one on each end of the test cavity, so that S_{11} (reflection) and S_{21} (transmission) measurements can be performed with a vector network analyzer.

SUMMARY

We are well along the way to achieving the goals of this project. We have already attained susceptibilities in our active test materials that are larger than were originally expected. The new permanent magnet dipole design will simplify construction and operation of the bench test apparatus and with a modified test cell should be able to form the basis of the acceleration experiment.

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