PROGRESS TOWARDS AN EXPERIMENTAL TEST OF AN ACTIVE MICROWAVE MEDIUM BASED ACCELERATOR*

Alex Kanareykin#,Euclid TechLabs LLC, Solon, Ohio, USA
Paul Schoessow†, Tech-X, Boulder, Colorado, USA
Levi Schächter, Technion, Haifa, Israel

Abstract

We have been working on an experimental test of the PASER [1] concept, where an active medium is used to provide the energy for accelerating charged particles. Initial theoretical work in this area focused on acceleration at optical frequencies; however we have identified a candidate active material operating in the X-band: a solution of fullerene (C_{60}) in a nematic liquid crystal has been found to exhibit a maser transition [2] in this frequency range. The ability to employ a microwave frequency material simplifies the construction of test structures and allows beam experiments to be performed with relatively large beam emittances. We will report results on synthesis and testing of the active material using EPR (*Electron Paramagnetic R*esonance) spectroscopy, design and numerical simulations of bench test structures and plans for future beam experiments.

INTRODUCTION

Perhaps the most common method of accelerating charged particles involves the transfer of energy from a standing or traveling electromagnetic wave in a resonant structure to the beam. At microwave frequencies klystrons or similar vacuum electronic devices are used to energize the structure. At optical or infrared wavelengths the use of lasers either to power a resonant structure or a plasma [7] has been the subject of extensive research. The direct transfer of energy to a particle beam from a pumped active medium (PASER) has also been proposed [1]. In this technique the coherent radiation source is incorporated into the accelerating structure.

The PASER effect is not limited to optical frequencies: a PASER operating in the microwave regime requires only a suitable maser material as a power source. Classical active maser materials such as ammonia or ruby are disfavored for PASER applications because of their low energy densities and cryogenic operating temperatures. The observation of microwave activity in near-room temperature paramagnetic media using EPR spectroscopy [2] offers the possibility of developing a practical X-band PASER.

The frequency of the maser transition in a paramagnetic spin system relation will occur in the neighborhood of the EPR resonance. The resonance condition is $\nabla\omega=g\beta H$, where ω is the Larmor frequency, β is the Bohr magneton, and H is the applied magnetic field strength. The gyromagnetic ratio is defined as $\gamma=g\beta/\nabla$, with $1<g<2$ depending on the spin-orbit interactions in the material. Typically EPR spectra are obtained by holding the frequency of the rf source constant and sweeping the applied magnetic field (H~3000 Oe for λ~3 cm). The linear relation between the applied field and the resonant frequency suggests that tuning a PASER device based on a paramagnetic material can be accomplished by adjusting the magnetic field strength.

*Work supported by US-DOE
alexkan@euclidconcepts.com
† Current address: Euclid TechLabs LLC, Solon OH USA

MICROWAVE ACTIVE MEDIA

Three-level solid-state maser amplifiers based upon the paramagnetic properties of the unpaired electron exploit changes in the electron spin population of the magnetic Zeeman levels, thus allowing amplification of electromagnetic radiation in the bulk material [3]. To achieve amplification in a paramagnetic based maser, an inverted spin population must be achieved, corresponding to a negative spin temperature. The population difference ΔN between the spin levels is directly related to χ'' (the imaginary part of the magnetic susceptibility) which is indirectly measured in EPR experiments.

The C_{60} molecule in its ground state is not EPR active. Following photoexcitation of C_{60} in solution by a short pump laser or flash lamp pulse an EPR active triplet state can be formed. The EPR spectra and activity of C_{60} are strongly dependent on the solvent used. In ordinary non-ordered solvents like toluene, there is no zero field splitting of the triplet state. The unsplit state can only exhibit a single absorption line at $\omega_0 = \gamma H_0$.

If the solvent exhibits a long range 1D order, such as a nematic liquid crystal (LC), the symmetry breaking introduced by the solvent causes the local electric and magnetic fields to no longer average to zero. The triplet state in each excited fullerene molecule now undergoes a Zeeman splitting into three levels. If the spin energy levels of the fullerene triplet state become selectively populated, stimulated emission can occur.

There are several possible mechanisms to create the population inversion and control the electron spin polarization generated in photoexcited chemical systems. One approach, to control ΔN via photoexcitation, was described in [2]. The optical pulse serves in this case both to generate the EPR active triplet state and to create the population inversion by exciting the electrons from the lowest Zeeman level into the uppermost. The other mechanisms fall into the category of chemically induced dynamic electron spin polarization (CIDEP). In these cases the inversion is not formed directly by optical pumping but results from the interaction of the excited

$*^3C_{60}$ with another photoexcited species in the solution [5].

We have synthesized a number of C_{60} based candidate active materials. Using EPR spectroscopy we have characterized the activity of the media as a function of the LC solvent type, the C_{60} concentration, and the concentration of additional solutes like porphyrins. We will briefly summarize the results here: more detailed results can be found in [8].

Figure 1 [8] shows some representative time resolved EPR spectra for two fullerene-liquid crystal active materials. Also shown are spectra of reference samples of C_{60} in toluene, a solvent that does not possess any long range order. The reference samples show a single narrow EPR absorption line, while C_{60} dissolved in the liquid crystal E7 (Merck) exhibits both absorption and emission characteristics depending on the magnetic field. (Other commercial nematic LCs used as solvents did not perform as well as E7.)

The addition of Tetraphenylporphyrin (TPhP) was found to improve both the spin density and the gain bandwidth of the material [8]. C_{60}–E7 exhibited the previously reported amplification bandwidth (FWHM) of ~ 40 MHz, while a 1:1 mixture of C_{60} and TPhP in E7 demonstrated an extremely large bandwidth EPR spectrum of 360 MHz for both emission and absorption lines. The selective population results in a situation with both underpopulated and overpopulated spin states, which in turn will generate either positive or negative imaginary spin susceptibility depending on the dc magnetic field. The spin density of the TPhP material (proportional to the amplitude of the spectrum is larger by a factor of ~1.5 over the C_{60}–E7 alone.

The stored energy in the active material can be estimated by taking the product of the spin density in the inversion and the energy of the maser transition, or roughly

$$\Delta n \times h\nu \sim (10^{17}\, cm^{-3})(6.6\times10^{-27}\, erg\cdot s \times 10^{10}\, Hz) = 6.6\, erg\, cm^{-3}$$

Further assuming about 1 cm^3 of active material per linear *cm* of accelerator, we get an accelerating gradient of 660 *keV /cm* assuming 1 *pC* of charge in the bunch, 100% energy transfer efficiency, and no dielectric or wakefield losses in the medium. Similarly, assuming a spin relaxation time $\sim 1\,\mu s$, the power density of the medium is $\sim 0.66\, W/cm^3$.

It is important to note that there is no fundamental reason why the spin density (and consequently the stored energy) cannot be increased further by several orders of magnitude. The currently attainable spin density is measured in solutions where the fullerene concentration is $\sim 10^{-3}\ Mol/l$. At larger concentrations there is a tendency for the C_{60} molecules to form clusters; we are currently investigating alternative choices of solvent and preparation technique to ameliorate this. We have already improved the bandwidth of the maser amplifier by almost a factor of ten, through the use of a C_{60}–porphyrin mixture. It is also worthwhile to point out that the media that we have been studying, being liquids, should with further development be able to perform favorably compared to the gas lasers originally suggested for powering the PASER simply on the basis of energy density arguments.

MICROWAVE PASER EXPERIMENTS

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 accelerating structure containing the active medium must be supplied with pump energy from a flash lamp or laser and also maintained in a uniform magnetic field of about 3 kG for X-band operation. We have been considering several possible geometries for PASER and related active medium experiments that we summarize here.

Initial efforts will be devoted to bench tests of the microwave PASER concept. At present all of the measurements of active media discussed in this proposal have been performed using very small samples in EPR spectrometers. We have developed a design for a system to study active media loaded resonators with standard microwave test instruments. The bench test apparatus must be capable of exciting a quantity of active material using a high intensity flash lamp while the sample is immersed in a fairly uniform magnetic field. The active material needs to be contained in a resonant cavity with pickups for both forward and reflected power measurements. Finally the material sample must be cooled.

Fig. 2 shows a sketch of the proposed bench test system. An elliptical cell fabricated from aluminum serves both as support for the test cell and flash lamp, while its interior mirrored surface concentrates the light from the flash lamp onto the test cell. The cell dimensions allow it to be mounted inside the bore of an existing solenoid that provides the magnetic field for the paramagnetic resonance. The flash lamp and test cell are mounted at the foci of the ellipse. Endcaps on the cell will provide mechanical support for the test cavity and flash lamp. Two ports are provided, one on each endcap of the test cavity, so that S_{11} (reflection) and S_{21} (transmission) measurements can be performed with a vector network analyzer. A complementary approach is to mix the X-band signal with a local oscillator and diagnose the resulting rf pulse with a fast digital oscilloscope.

A number of options are presently being evaluated as the basis of a beam acceleration experiment. (1) The "classic" configuration, in which a single bunch is accelerated by an extended volume of material. The medium is not enclosed in an rf structure resonant at the frequency of the maser transition. A narrow quartz capillary serves as a beam channel.

(2) The wakefield amplifier. A relativistic "harbinger" beam generates a wakefield in a cylindrical dielectric structure similar to the collinear dielectric wakefield accelerator. The wakefield is amplified by the active medium which is tuned (by adjusting the magnetic field

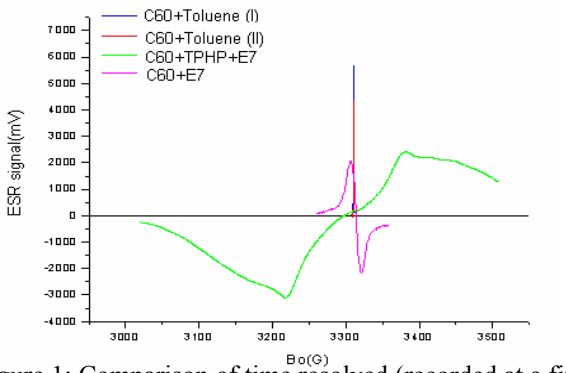

Figure 1: Comparison of time resolved (recorded at a fixed delay with respect to the laser pulse) EPR spectra for some of the test samples. Positive signal corresponds to absorption, negative to emission. 1G = 2.8 MHz; the position of the reference absorption peaks corresponds to 9.27 GHz [8].

strength) to have its maser transition at the fundamental luminal TM_{01} frequency of the structure. Fig. 3 shows a comparison of the longitudinal wakefields in a dielectric active structure showing the effects of paramagnetic gain and dielectric losses using the Arrakis [6] code. The structure geometry is close to that of the bench test resonator: inner radius 7 mm, outer radius 12.5 mm. The structure was loaded with an active medium with ε = 2+0.01i, Lorentz permeability, and gain bandwidth = 180 MHz. The frequency dependent permeability is treated numerically using the auxiliary differential equation approach [4]. The inversion spin density (proportional to the gain) was scaled by a factor of 10^3 over the estimates in [2] and represents a reasonable extrapolation of the eventual performance of this class of materials.

(3) Combined active-copper/dielectric structures. The active material is integrated into an iris loaded (or more complex) resonant structure. Possible advantages of this geometry are the ability to control the magnetic vs electric field strength in the volume of the active medium to minimize dielectric losses, and the ability to move the

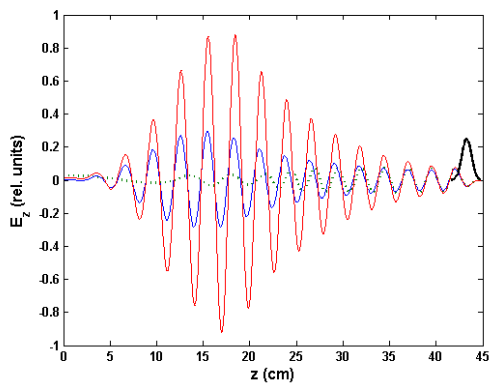

Figure 3: Arrakis simulation of the longitudinal wakefield of a beam in an X-Band dielectric structure. Black: beam pulse; Green: wake from passive dielectric; Red: active structure; Blue: active structure with lossy dielectric.

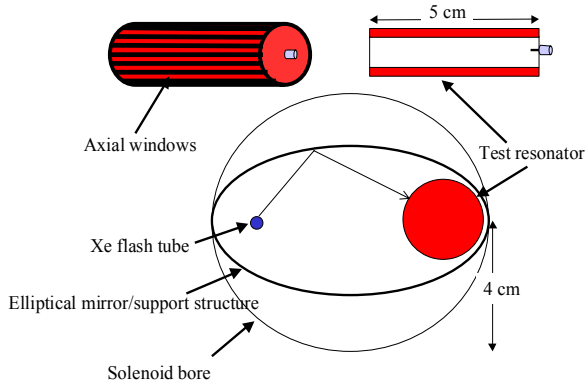

Figure 2: Sketch of the bench test system.

medium (and the magnetic field) away from the beamline.

A number of possible geometries are under consideration. One challenge is providing the 3 kG magnetic field for the medium over the volume of the structure, while at the same time allowing the optical pump pulse to illuminate the structure.

SUMMARY

A number of chemical systems, consisting of C_{60} molecules and porphyrin molecules dissolved in organic solvents or embedded in liquid crystals were synthesized and studied via EPR spectroscopy as candidate active materials for a microwave PASER experiment. The measurements show that $^{*3}C_{60}$-TPhP complexes in liquid crystal solution are better active materials in terms of spin density and bandwidth than C_{60}-E7—a factor of 1.5 in gain and a factor of ~10 in bandwidth. Further performance improvement is expected.

A design for a bench test experiment to study the properties of the active media inside a prototype accelerating structure was presented. A number of different options for performing an accelerator measurement of acceleration of injected beam were described and are currently being evaluated.

REFERENCES

[1] L. Schächter in Advanced Accelerator Concepts AIP Conf. Proceedings 335, P. Schoessow ed. (1995).
[2] A. Blank et al. IEEE Trans. Microwave Theory and Techniques 46 (2137) 1998. Blank A, Levanon H, Appl. Phys. Lett. 79: (11) 1694-1696 2001.
[3] N.Bloembergen, Phys.Rev., vol.104, p.324, 1956.
[4] P. Schoessow, A. Kanareykin, Proc. 2005 PAC, http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/TPAE033.PDF.
[5] F.J.Adrian, J.Chem.Phys., 54, p.3918, 1971. C.Blattler et al., Chem.Phys.Lett., 166, p.375, 1990.
[6] P. Schoessow, W. Gai, in Quantum Aspects of Beam Physics, P. Chen ed., World Scientific 1999.
[7] T. Katsouleas, Nature 431, 515 - 516 (2004).
[8] E.Bagryanskaya, N. Yevlampieva et al., to be published in the Proceedings of the 2006 Advanced Accelerator Concepts Workshop.