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# AN OPTOFLUIDIC PHOTOBIOREACTOR STRATEGY FOR BIOENERGY

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## ABSTRACT

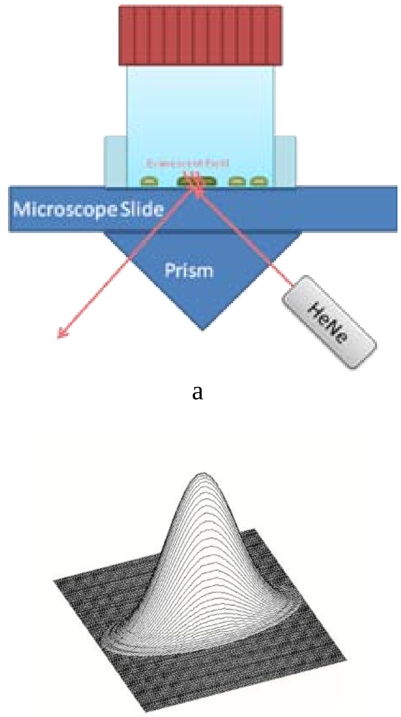
A novel approach to cultivating cyanobacteria is presented which utilizes near-field evanescent waves on the surface of waveguides to excite the photocenters in the thylakoid membranes of cyanobacteria. This approach to light delivery when applied to photobioreactor design may provide an opportunity to significantly increase yield and make biofuels an economically competitive alternative to traditional fossil fuels.

## INTRODUCTION

Growing concern over climate change and fossil fuel supplies has led to greater interest in alternative energy sources[1]. Of the options available solar energy is by far the most abundant. Over 2.7 billion peta joules (PJ = $10^{15}$ J) of solar energy is incident on the earth's surface per year, dwarfing global energy demand of 472 thousand PJ [2]. Significant advances have been made in capturing this energy both passively and actively through photovoltaic and solar thermal technologies. However, electricity as an energy carrier is difficult if not expensive to store, particularly in large volumes for sustained periods of time. Fuels have long been recognized for their high energy density and applicability to a unique, yet significant subset of our energy needs, including transportation and heating. As a consequence, our reliance on petrochemical based fuels has accelerated global changes to global temperatures currently being observed. Alternative liquid fuels that are competitive economically and energetically with fossil fuels that do not impact atmospheric carbon levels are necessary.

Of the alternatives to petroleum based fuels, microalgae based biofuels show significant promise towards substantially displace our reliance on fossil fuels for transportation [3]. Microalgal biomass exhibits high growth rates and fuel densities that are orders of magnitude greater than any other crop plant [4]. Furthermore, their cultivation does not compete with food crops for arable land and can be grown harvested in regions and environments inhospitable to most other plants. Consequently, much attention is being given to increasing the efficiency of microorganisms to generate both biomass and direct evolution of usable fuel [5]. Cyanobacteria, a particular type of photosynthetic bacteria, are of particular interest as most require only $CO_2$ and water to grow, with minimal amounts of other nutrients [6]. This has benefits from both a cost and emissions perspective as fuel produced from such organisms comes very close to being carbon neutral. Concurrently, advances in photobioreactor design and characterization of their yield potential have been pursued. However, as of yet, a commercial scale solution that can compete with the comparatively low price of fossil fuels has yet to be realized [7].

Here we demonstrate a novel method to improve light distribution in PBRs that may enable a paradigm shift in the way that PBRs are designed. This approach takes advantage of near-field evanescent waves on the surface of waveguides to stimulate the thylakoid membranes of cyanobacteria directly adjacent to the surface of the waveguide. When applied to photobioreactor design on a large scale, this technique would provide a means to excite bacteria optimally, and pack bacteria at high density within the reactor, addressing many of the key challenges posed by current photobioreactor architectures. Growth of photosynthetic organisms in response to an evanescent field has not been demonstrated previously in literature, and is the focus of this work.




a

b

**FIGURE 1**. Schematic of evanescent illumination and cultivation strategy. Evanescent coupling of *S. elongatus* via total internal reflection at the surface of a prism (a) and the evanescent field intensity profile at glass/media interface (b).

Figure 1 shows the experiment designed to demonstrate the feasibility of this approach. In it, an evanescent field is generated by passing laser light from a 1 mW helium-neon laser ($\lambda$ = 632 nm) through a prism. The area around the evanescent field is inoculated with cultures of *Synechococcus elongatus* (ATCC 33912) a pill shaped, immotile cyanobacteria. The cultures are kept in isolation from external light by placing the apparatus in an enclosure made of 1/16" thick black poster board panels and left for three days.

Cavities to contain the bacteria culture solution were fabricated by removing the bottom of laboratory test tubes and mounting them to the surface of a 1 mm thick BK7 glass microscope slide using epoxy. Total capacity was 5mm.

Once mounted to the glass slides and inoculated, the culture was placed on the top face of a right angle BK7 prism, as shown in figure 1. Optical contact was achieved using an index matched immersion oil. Light was coupled to the chamber from the laser directed toward the prism by reflecting it off a broadband dielectric mirror housed in a precision rotation mount.

Figure 2 shows resent results obtained. Preferential growth of *S. elongatus* is shown in the region where the beam was incident on the surface of the slide. Power output measurements indicated total internal reflection occurred, and the evanescent field was present. The green coloration of the

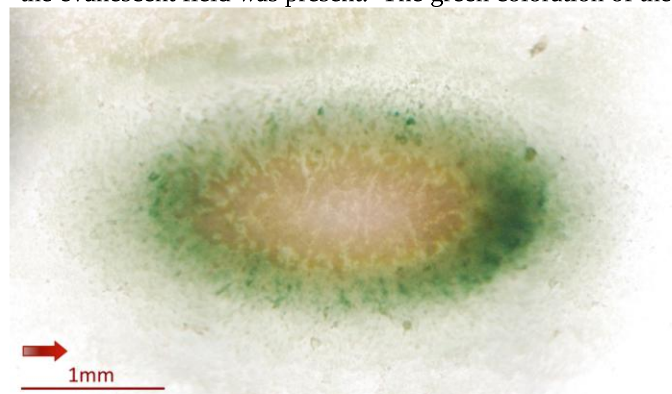



**FIGURE 2.** Composite brightfield image showing localized growth in the evanescent field on glass-water surface - see Figure 1b.

elliptical ring pattern suggests higher concentrations of chlorophyll which can be attributed to higher viable cell concentration. It can be concluded that optimal conditions for growth occurred in the peripheral regions of the evanescently illuminated area.

The beam of the HeNe laser used has a nearly Gaussian profile and consequently the intensity of the incident beam and associated evanescent field is highest in the centre of the ellipse decreasing towards the periphery as shown in figure 1b. It is hypothesized that little growth was observed within the border of the green elliptical pattern because the intensity of the field in this region was too great (incident light level on the order of 500 W/m$^2$ @ 632 nm). The faded coloration is suggestive of cells that have become photoinhibited, a condition in which their ability to repair damaged pigments is overwhelmed by the rate at which they are being damaged by the intensity of the light [8].

Further experiments based on models developed in Matlab are underway to vary the growth patterns by controlling the intensity of incident light and the angle of incidence of the laser beam. Demonstration and characterization of the preferential growth rings with respect to these two control variables will allow for a more detailed understanding of growth in more complex waveguides.

In conclusion, initial experiments with evanescent illumination of cyanobacteria demonstrate preferential growth of bacteria in the evanescent wave. Future experiments will help to better characterize the potential impacts of both field intensity and incident angle to validate theoretical predications based on the model developed.

This approach to cultivating photosynthetic microorganisms represents an initial step in a new paradigm in photobioreactor-based biofuel generation. By supplying light for photosynthesis at a cellular level using evanescent fields rather than bulk irradiation, targeted delivery of energy can be achieved helping to overcome some of the central challenges of light delivery and biomass density in PBR designs.

## ACKNOWLEDGMENTS

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