Sun to Fiber: a thin film optical funnel for energy conversion and storage

Matthew Garrett, Juan J. Díaz León, Kailas Vodrahalli, Taesung Kim, Ernest Demaray, Nobuhiko Kobayashi

Department of Electrical Engineering, University of California, Santa Cruz
Advanced Studies Laboratories, NASA Ames Laboratory
Outline

• Discuss energy needs that inspire the Sun to Fiber (S2F) coupler
• Propose our solution to meet these energy needs
• Possible approaches for this coupler
• Our specific design chosen for the coupler
• Collaborations and large-scale implementation plans
Reasons to Transport Sunlight

- **High daytime electricity usage**
- **Solar concentrators for solar thermal**
- **Only works when the sun is shining locally**

Many energy needs could be met by moving sunlight to where it’s needed.
Smaller Scale Uses For Sun to Fiber

Solar heat to create biochar fuel in developing countries

Lighting for underground Mars base

The ability to concentrate and transport sunlight will improve third-world fuel & sanitation, and reduce energy needs during space exploration.
Proposed Solution

- Optical Waveguides for transporting Solar Energy (‘S2F’ Project)
  - Concentrate with Parabolic Mirrors or with Lenses
  - Optical Waveguide/Coupler: Capture; Focus & Transport; Couple to Fibers
  - Optical Fibers: Transport

S2F coupler will capture, focus, and direct solar energy into fiber optic cable, for direct use or conversion where needed.
Our Design:
Planar Tapered Waveguide
Waveguides for datacom/telecom
- Single-wavelength
- Fiber input, chip output
- ~500 um length
- Semiconductors for transparency at certain lasing wavelengths outside the visible spectrum

Waveguides for clean energy
- Broadband
- Thin film input, fiber output
- ~1-100 cm length
- Metal Oxides for visible spectrum transparency

Waveguide tapers are not new, but guiding broadband, visible spectrum light requires new innovation
Reactive Scanning Magnetron Sputtering with AC Substrate Bias

This method yields a uniform film, with precise control over stoichiometry, crystallinity/amorphousness, and index of refraction.
Angle Dependency of Taper

Taper must be over five times as long as it is wide to achieve >90% efficiency.

Works only if \( L > 5W \).
One shape-changing approach

Straight Taper
50% output efficiency

Irregular Taper
86%-92% output efficiency from $\lambda = 1300\text{nm}-1700\text{nm}$

Felici et al. LEOS 2002

Non-intuitive shapes can increase the amount of input light guided into the fiber, but is still very wavelength dependent
Index Grading Approach

If we do not want to make $L \gg W$, then a non-uniform core index can increase efficiency, without changing waveguide geometry.

Laterally graded index with uniform index vertically, increases efficiency to 75%
Index graded both vertically and laterally, with matching to the fiber core, yields 96% efficiency across the visible spectrum.
Specific Applications
Indoor Solar Daylighting

Effective rooftop sunlight capturing systems have already been developed by the Himawari Corporation.
S2F coupler for the Himawari system

- S2F coupler will reduce the need for 12 Fresnel to only one larger lens.
- Highly directed light from the S2F coupler permits use of low numerical aperture fiber, and also reduces the number of fiber optics needed.

Himawari-UCSC collaboration with NASA Ames Sustainability Base will improve upon this promising technology.
Problems with Concentrated Solar Power

A common set of problems across technologies

High emission losses

High working fluid transmission losses

High thermal conversion losses because of low $T_{\text{working}}$

S2F Coupler can improve all types of concentrated solar power systems
The S2F coupler can be used for high-power energy conversion.
Cost analysis of an S2F solar plant compared to a power tower

SAM Model Comparison: Power Tower & S2FC - 115 MW Plant

- 70% smaller heliostat field
- Lower total system cost
- Enables substantially lower economic system size with goal of 20 – 50 kW
- Potential for easy diversion of power to storage

Electricity generated with S2F technology is predicted to cost <75% of current state of the art solar thermal technology
Conclusions

• We have designed and modeled a planar optical waveguide coupler transformer

• The effective coupler utilizes thin metal oxide films, with high visible spectrum transparency

• These films rely on a graded index of refraction and a tapered shape

• The coupler allows broadband light to be directed, with near-zero loss, into fiber optic cable, and transmitted away from the point of collection

• Captured light can be harnessed for daylighting, electricity generation, or for storage thermally or as synthetic fuels