

Er-doped planar waveguides for power amplifier applications

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Keywords: Optical Materials, Tellurite, Erbium, Erbium/Ytterbium, Laser amplifier, CO₂

ABSTRACT:

New devices are required to provide effective tools for DIAL or LIDAR measurements from space, which will enable improved mapping of the concentration and distribution of CO₂ in our atmosphere. Here we present characteristics of Er-doped thin film waveguides, with an extended gain bandwidth, which are applicable to planar waveguide power amplifiers for wavelengths around the 1572 nm CO₂ absorption peaks. Planar waveguide films have been fabricated by sputtering of fluorophosphate and tellurite based glasses onto oxidised silicon wafers, and their properties characterized. The deposition parameters for undoped and Er,Yb-doped films have been assessed and studied, achieving losses of <1.5 dB/cm at 633 nm for the as deposited waveguides. A comparison between the two host materials is made and the potential performance discussed.

1. INTRODUCTION

There is an imminent need to study the concentration carbon dioxide (CO₂) in the atmosphere of our planet, currently at its highest level than at any time in the past 0.4M years. To do so the appropriate tools have to be developed that meet the needs for gathering sufficient data to produce models that better describe the nature and processes of CO₂ sinks on a global scale. One approach, is the ASCENDS mission scheduled to be launched by NASA's Goddard Space Flight Centre later this decade, which will use an efficient tuneable MOPA source seeded by pulsed narrow-linewidth diode-lasers for laser sounding and altimetry of key tropospheric greenhouse gas abundance from space, continuously measuring at all times of the night and day throughout the year [1].

In this paper we detail our investigation of thin films of erbium-doped tellurite and fluorphosphate glasses intended for a planar waveguide power amplifier module. These glasses have the potential to provide gain at wavelengths beyond the traditional telecommunications C-band that overlap the CO₂ absorption line around 1572 nm. Fabrication of the thin films via sputtering has already shown good potential for erbium-doped tellurite [2, 3], which should be able to provide significantly larger active mode-areas than fibre based amplifiers. As such limiting non-linear processes (i.e. Stimulated Brillouin Scattering and Stimulated Raman Scattering) can be mitigated and enable higher peak powers despite the very narrow linewidth requirement for gas spectroscopy. Moreover due to the higher emission cross section offered by these glasses with respect to silicates [4, 5], there is the potential to make a more compact gain-module for the power amplifier stage in a MOPA system. To date in our samples we have measured, with in-band pumping at approximately the saturation irradiance for the glasses, gains in excess of 2 dBcm⁻¹ at the 1535 nm peak and 0.7 dBcm⁻¹ around 1572 nm the key wavelength of interest.

2. METHODOLOGY

2.1 Materials selection

Er-doped silicates have a relatively narrow emission band (FWHM \approx 30 nm) peaking around 1530 nm and therefore are not suitable for the application of interest. Er-doped fluorphosphate and tellurite glasses however, are more interesting due to their broad and strong gain band (up to FWHM \approx 70 nm) with an emission tail that extends beyond 1600 nm. The modest phonon energy of fluorphosphate glasses (\sim 1100 cm⁻¹) facilitates efficient energy transfer rates in Er/Yb co-doped glasses suitable for 980 nm pumping, while ensuring reasonably fast non-radiative decay (due to multi-phonon relaxation) between

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the Er^{3+} ions $^4\text{I}_{11/2}$ and $^4\text{I}_{13/2}$ energy states. Moreover, the lifetime of the level of interest $^4\text{I}_{13/2}$, is not significantly quenched as at least five phonons are required to bridge the energy gap to the ground state. Tellurites glasses on the other hand typically have phonon energy levels $<800\text{ cm}^{-1}$, meaning the $^4\text{I}_{11/2}$ level of Er^{3+} ions has a modest lifetime that can allow back-transfer of energy to a Yb^{3+} co-dopant, alternatively the stored population in this level can be extracted parasitically via excited state absorption (ESA), energy transfer upconversion (ETU), or simply radiatively to the ground state. Presented last year at this conference [6] we explored Teullurite compositions based on a zinc oxide glass former, magnesium oxide modifier, and borate additive to capitalise on the more energetic stretching vibrations of the B-O bonds [7], up to about 1400 cm^{-1} . This indeed assisted efficient absorbed pump energy transfer by Yb^{3+} to Er^{3+} , however it was at the expense of the $^4\text{I}_{13/2}$ level lifetime, reducing it to $\sim 3\text{ ms}$. In this study it was elected to pursue in-band pumping around 1480 nm , thus having a low phonon energy host can be beneficial for maximizing the radiative lifetime of the $^4\text{I}_{13/2}$ energy. As such we chose to investigate an $80\text{TeO}_2 - 10\text{ZnO} - 10\text{MgO}$ (TZM) composition, without the borate additive. In addition we investigate the potential for fluorophosphates glass waveguide films, starting with a commercially available material.

2.2 In-band pumped gain measurements

Pump-probe gain measurements were made on bulk samples of the two glasses of interest, to determine the potential gain of each glass composition around 1572 nm . We employed a 500 mW 1480 nm fibre-coupled diode pump source (Furukawa electric FOL1435R50-617-1480), in pulsed-mode driven by an arbitrary waveform function generator (Tektronix AFG 3102), producing 10 ms pulses at a 2% duty cycle, thus avoiding any detrimental thermo-optical effects in the few mm thick samples. The output from the fibre-coupled diode was reflected by a high-pass dichroic filter and re-imaged into the sample with a beam diameter of $100\text{ }\mu\text{m}$, as illustrated in the schematic in Figure 1. The incident pump irradiance ranged between 1.6 kWcm^{-2} and 6.3 kWcm^{-2} . A CW tuneable diode source (Tunics Plus CL/WB) was used as the probe, the single mode fibre output was also reimaged into the sample, in the same direction and collinear with the pump, and with a matched beam waist, i.e. $100\text{ }\mu\text{m}$ diameter. The wavelength of the probe could be set between $1530\text{--}1580\text{ nm}$ with power levels up to 3 mW . The probe and residual pump beams were separated using a diffraction grating with 600 lines/mm , with the probe beam reimaged onto a large area Germanium detector (Thorlabs Model: SM1PD5B), shielded behind a 3 mm uncoated silicon window. The transmitted pump was focused down onto an InGaAs detector (Thorlabs DET10D-M), and the power change monitored for both pump and probe around the excitation pulse. Both photodiode output waveforms associated with the 10 ms pump pulse were recorded on a digital oscilloscope (Agilent MSO6104) at a range of probe wavelengths. The net gain for each sample was then calculated for the various pump intensities with respect to the un-pumped probe power prior to the start of the excitation pulse.

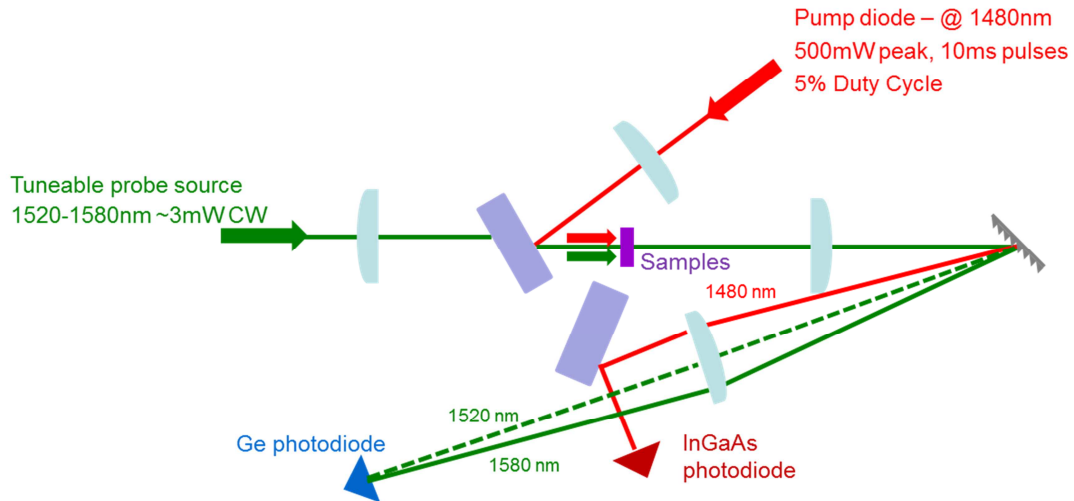


Figure 1. In-band pumping gain measurement setup.

2.3 Fabrication and characterization of the thin films

Two techniques were explored for fabricating thin films of the respective glasses. The first Radio Frequency (RF) magnetron sputtering, employing an OPT Plasmalab400 system, and the second, Ion Beam sputtering (IBS) using an OPT Ionlab 300 Plus system. Both of these systems require 6" diameter targets of around 5mm thickness. New targets were made for both of the glasses of interest. Two MM4 fluorophosphate glass billets, purchased from Kigre Inc., one un-doped and the other doped with 2.2wt% Er_2O_3 and 2.5wt% Yb_2O_3 , were reformed into 6" disks and mounted on copper backing plates for the sputters. A similar set of targets for the tellurite TZM composition were purchased from a commercial vendor made via a hot-press technique, one of which was doped with 1.5wt% Er_2O_3 and 1.5wt% Yb_2O_3 .

1mm thick 4" silicon wafers with a 2.5 micron thermal oxide layer were used as the substrates for the films. Room temperature deposition was performed in a partial pressure atmosphere of ~10mTorr with differing ratios of argon and oxygen flowing gases. After deposition, the thin films were characterized using a prism coupling system or ellipsometer system (Metricon - Model 2010 or J.A. Woollam M-2000) for their thickness and refractive index. In addition the surface quality and topology were measured using white light interferometry (Zemetrics - Zescope).

3. RESULTS AND DISCUSSION

3.1 Gain measurements

Measurements of the single-pass small signal gain was made at discrete wavelengths (5nm steps from 1530-1565 nm, then 1nm steps between 1567-1577 nm) in both the fluorophosphate (MM4) and tellurite (TZM) samples. At a maximum pump irradiance of 6.3 kWcm^{-2} and near-normal incidence on the uncoated samples, the highest observed gain at the 1535 nm emission peak was 2.1 dB/cm, from the TZM sample. The temporal evolution of the probe beam power associated with the 10 ms pump pulse was captured at each probe wavelength, revealing in some instances a spectral dependence on excited state energy transfer processes. Figure 2 illustrates the measured gain for the two samples, in-band pumped at 1480 nm, as a function of time at discrete probe wavelengths. A comparison of the gain for the same samples pumped at 974 nm is given in Figure 3, measured as per the setup described in [6]. Clearly the stronger absorption of the 974 nm pump provided a higher inversion and therefore higher gain. The longer lifetime of the $^4\text{I}_{11/2}$ level in the TZM glasses is evidenced by the excited state absorption lines around 1550 and 1570 nm seen in Figure 3, corresponding to a phonon assisted transition to $^4\text{F}_{9/2}$. Moreover, this is further supported by the much slower rise and decay time of the emission from the $^4\text{I}_{13/2}$ level, due to the additive effect of the energy transfer rate and lifetimes of the two lower Er^{3+} levels involved.

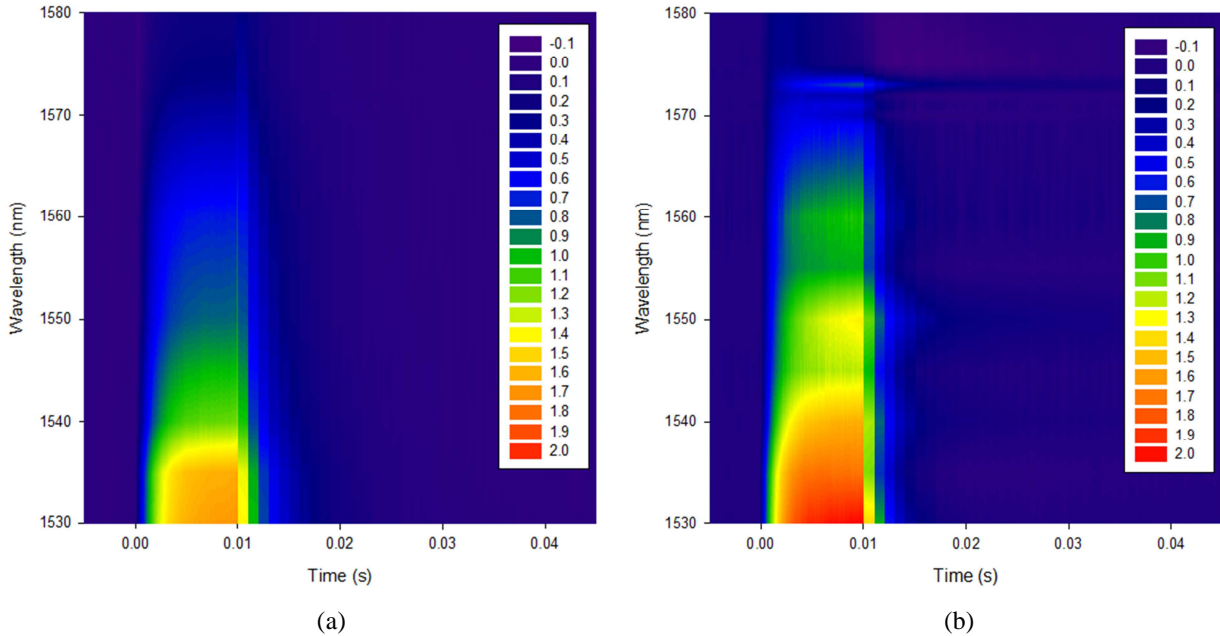


Figure 2. Gain in dBcm^{-1} for a 1480 nm pumped ($I_{\text{inc}} = 6.3 \text{ kWcm}^{-2}$) bulk samples (a) MM4 and (b) TZM.

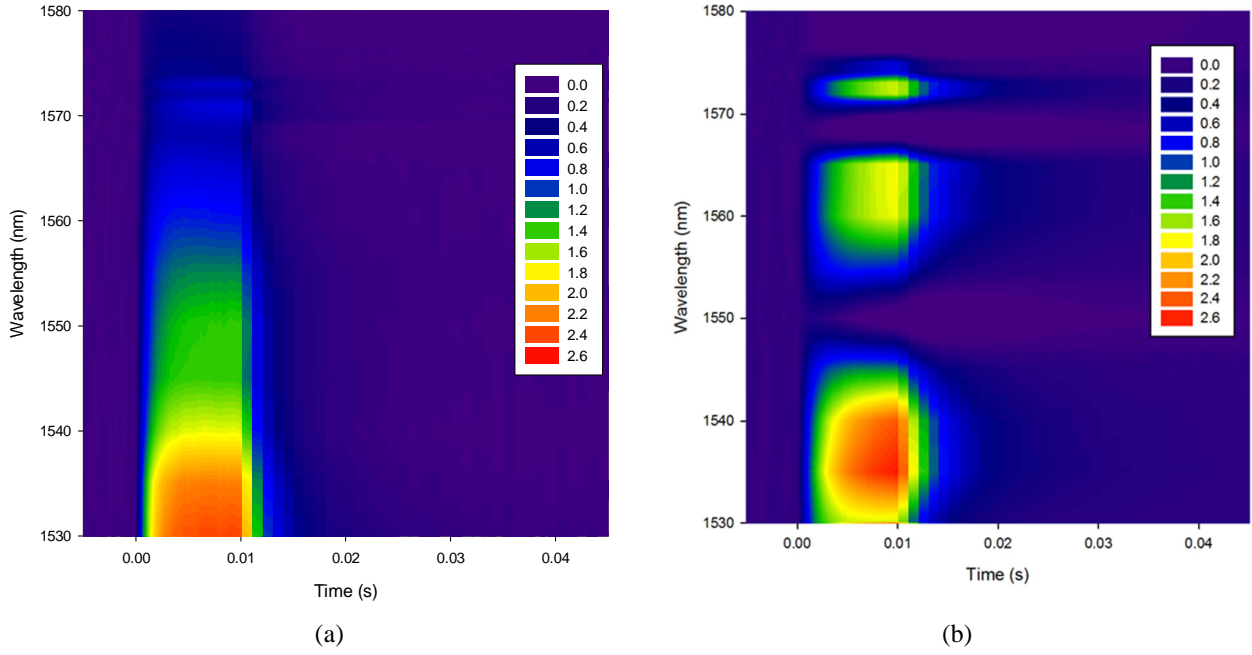


Figure 3. Gain in dBcm^{-1} for 974 nm pumped bulk samples ($I_{\text{inc}} = 4.7 \text{ kWcm}^{-2}$) (a) MM4 and (b) TZM.

3.2 Thin films and characteristics

MM4 films

Thin fluorophosphates films fabricated via RF sputtering were found to be high in refractive index, with respect to the raw materials $n_D \sim 1.565$, Figure 4(a), implying that the films were slightly metallic and the stoichiometry had not transferred from the target to the substrate. The growth rate of the doped/undoped MM4 films was on the order of $\sim 75/85 \text{ nm/hr}$ respectively. Films of $\sim 400 \text{ nm}$ were produced and found to support one or two modes at a wavelength of 633 nm . A simple study of the parameter space for RF deposition could not bring the refractive index in line with that of the target. Losses measured via prism coupling appeared to be in excess of 10 dBcm^{-1} further evidence of the slightly metallic nature of the film, as the film surface roughness was better than $S_q \sim 0.7 \text{ nm}$.

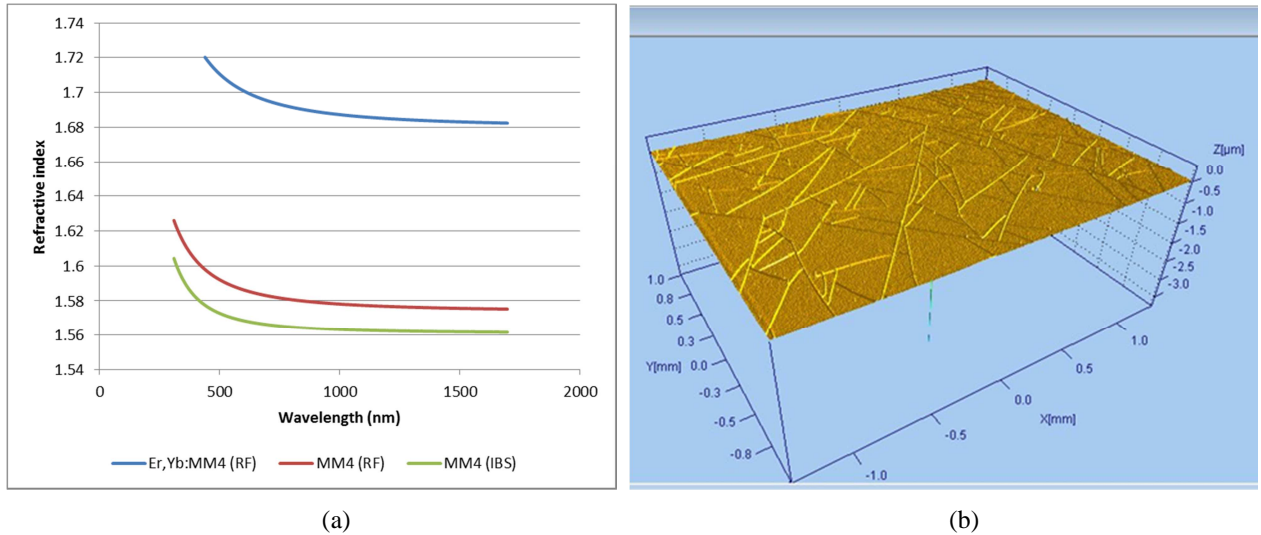


Figure 4: (a) refractive index for MM4 sputtered films. (b) “crazed” surface topology of $2 \mu\text{m}$ thick MM4 film by IBS.

IBS instead produced films with refractive index values closer to that of the target (Figure 4(a)); however, the rate of deposition was ~ 50 nm/hr. A full parameter space study is yet to be complete, however film thicknesses of ~ 200 nm were grown over a run of 4-5 hrs and their surface quality measured to be $S_q \sim 0.3$ nm. Such films were too thin to characterize with the Metricon system, therefore the ellipsometer was used to determine the film thickness and refractive index instead. An attempt to grow a thicker film of ~ 2 microns was made by doing 4 successive 5 hours deposition runs, unfortunately under the conditions tested the film was too stressed and “crazed”, Figure 4(b). No useful information about the glass film could be retrieved.

TZM films

RF sputtering with the TZM targets was tested and found to give a slightly lower refractive index with respect to that measured for the bulk glass sample, Figure 5(a), with its refractive index being around to 2. In addition the rate of deposition for these materials was much faster than for the MM4 films, i.e. doped/undoped TZM film growth rates up to $\sim 1000/1900$ nm/hr respectively were observed. A film thicknesses of up to 7.5 microns was grown in a 4 hour deposition and with films loss of $< 1.5 \text{ dBcm}^{-1}$. Figure 5(b) shows a typical TZM film surface topology with an S_q value of 0.3nm, this film had an as deposited propagation loss of 1.2 dBcm^{-1} .

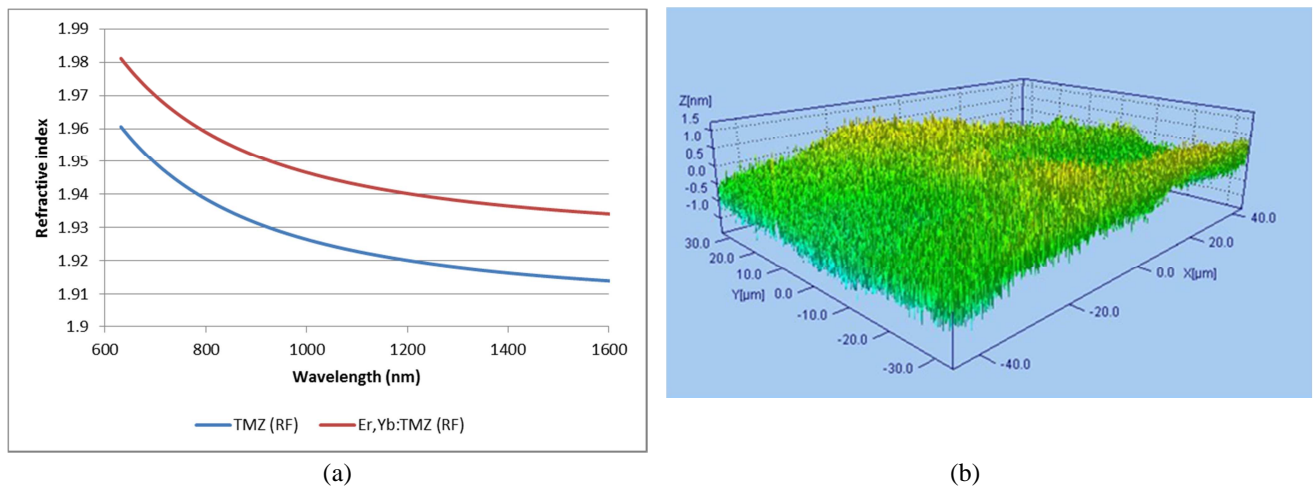


Figure 5: (a) refractive index for RF sputtered TZM and Er,Yb:TZM films. (b) surface topology of 4.5 μm thick TZM film by RF sputtering.

Finally to demonstrate the applicability of the TZM waveguides for high-power operation suitable for diode pumping, a pump-clad structure was grown. Consisting of three TZM layers grown on top of an oxidized silicon wafer, the pump-guide has a thickness of $\sim 13 \mu\text{m}$ and $\text{NA} > 1$, while the core is $4.3 \mu\text{m}$ with an $\text{NA} \sim 0.28$.

Undoped TZM $\sim 4.2 \mu\text{m}$
Er,Yb:TZM $\sim 4.3 \mu\text{m}$
Undoped TZM $\sim 4.4 \mu\text{m}$
SiO ₂ cladding $\sim 2.5 \mu\text{m}$
Silicon $\sim 1 \text{mm}$



Figure 6: Pump-clad TZM waveguide

4. CONCLUSION

We have reported the characterization and fabrication of fluorophosphates and tellurite waveguide films, targeting power amplifier applications in the wavelength band around prominent CO₂ absorption lines. Small signal gain coefficients in excess of 2 dBcm⁻¹ have been measured at the 1535 nm emission peak and 0.7 dBcm⁻¹ around the 1572 nm band of interest. We report to the best of our knowledge the first pump-clad TZM waveguide grown on a silicon wafer platform. The excellent surface quality of these films and thermal properties of the underlying platform support the potential for these waveguides to be operated at high average powers and with large mode-fill areas. Further work on these waveguides will determine the net gains achievable at the desired wavelengths, and these will be followed by the first demonstration of planar waveguide power amplifiers in these material systems.

5. ACKNOWLEDGEMENTS

The authors would like to thank NASA ESTO for the financial support of this effort.

6. REFERENCES

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