

## Electronic Supplementary Information

### Tuning the Chemical Properties of Europium Complexes as Downshifting Agents for Copper Indium Gallium Selenide Solar Cells

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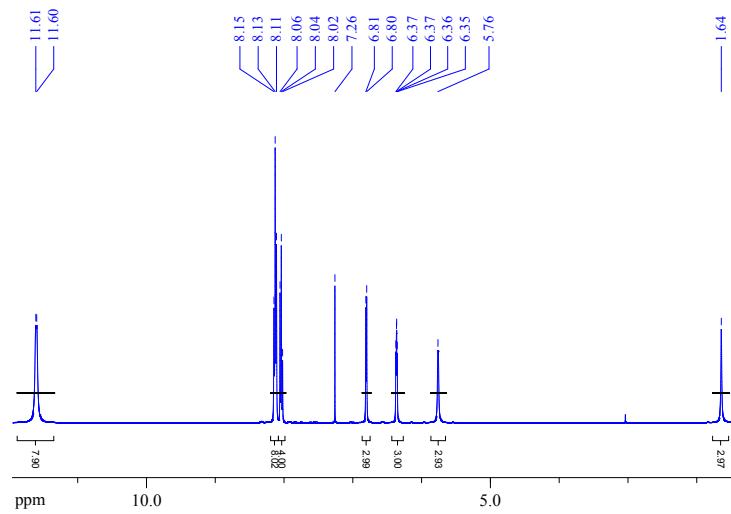
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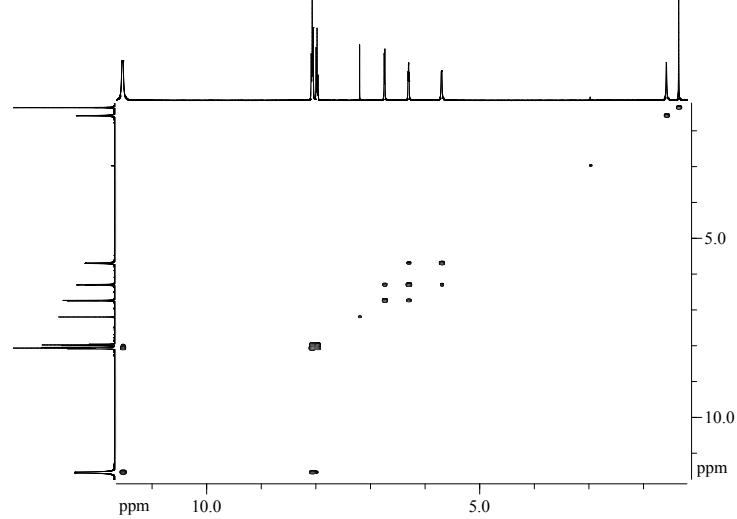
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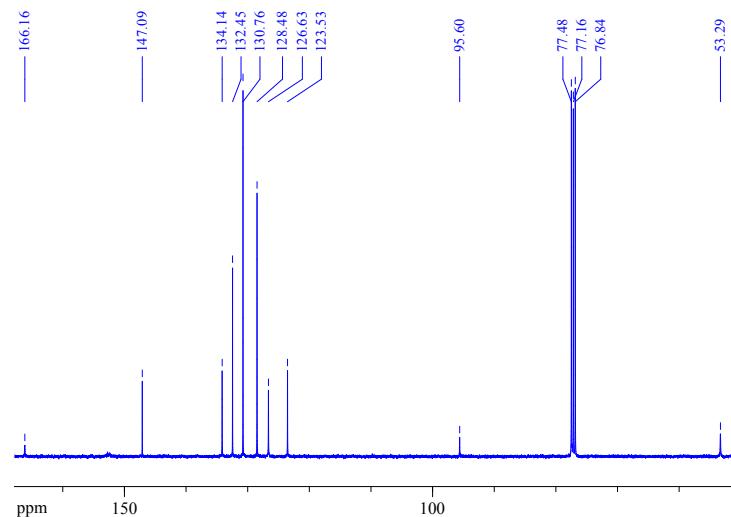
## NMR spectroscopy



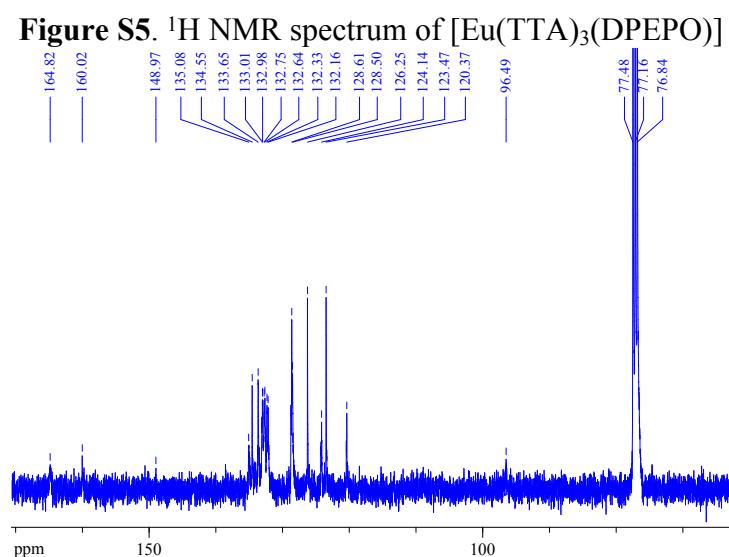
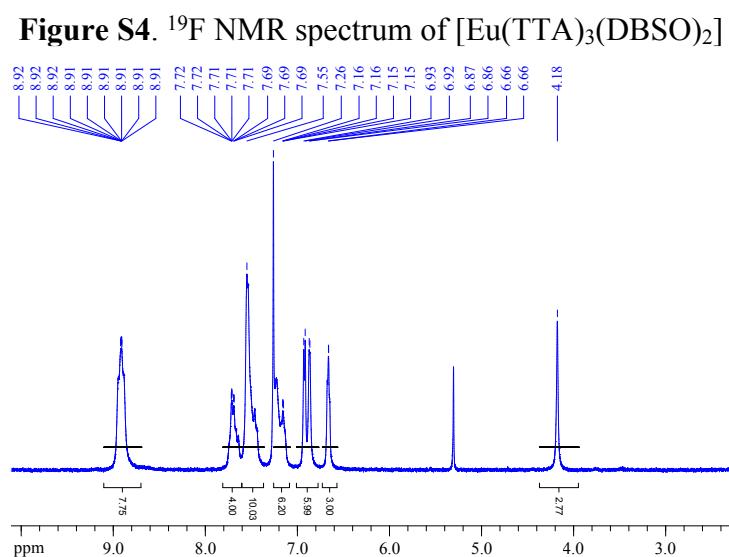
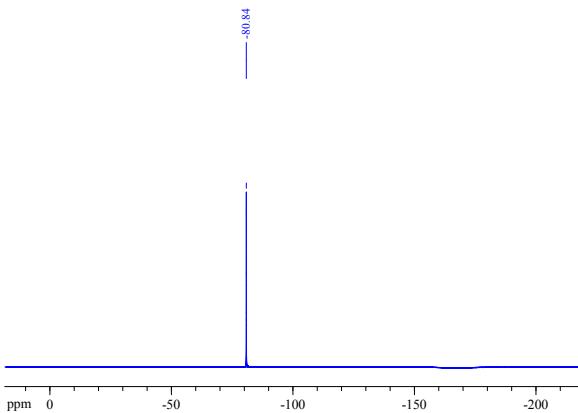
**Figure S1.**  $^1\text{H}$  NMR spectrum of  $[\text{Eu}(\text{TTA})_3(\text{DBSO})_2]$

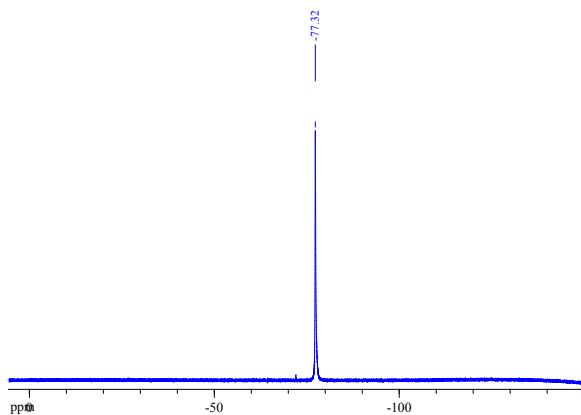


**Figure S2.**  $^1\text{H}$ - $^1\text{H}$  COSY NMR spectrum of  $[\text{Eu}(\text{TTA})_3(\text{DBSO})_2]$

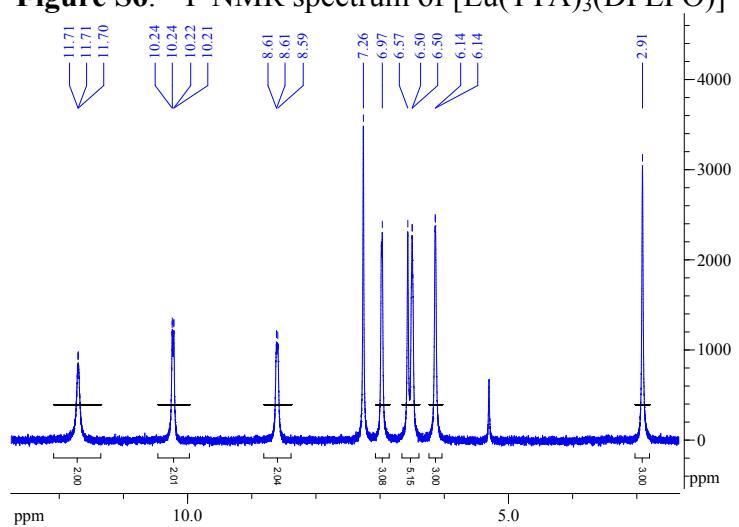


**Figure S3.**  $^{13}\text{C}$  NMR spectrum of  $[\text{Eu}(\text{TTA})_3(\text{DBSO})_2]$

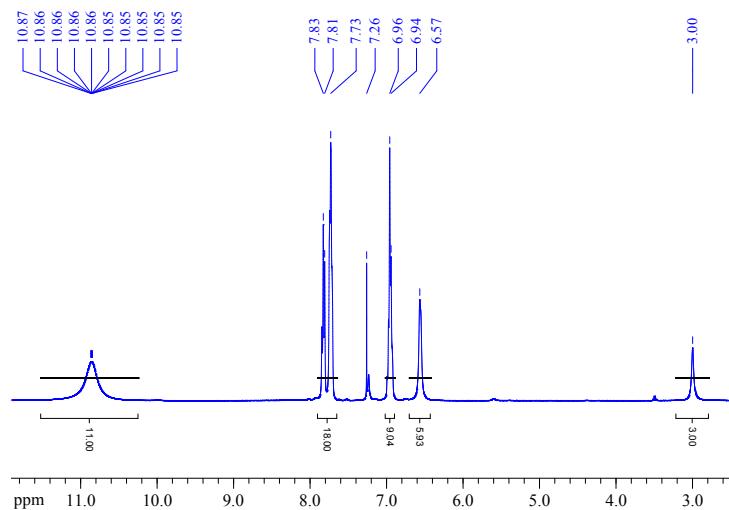




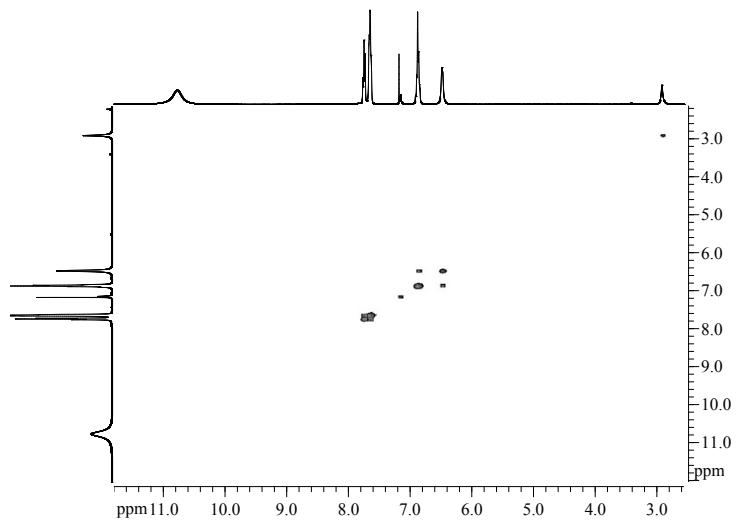
**Figure S6.**  $^{19}\text{F}$  NMR spectrum of  $[\text{Eu}(\text{TTA})_3(\text{DPEPO})]$



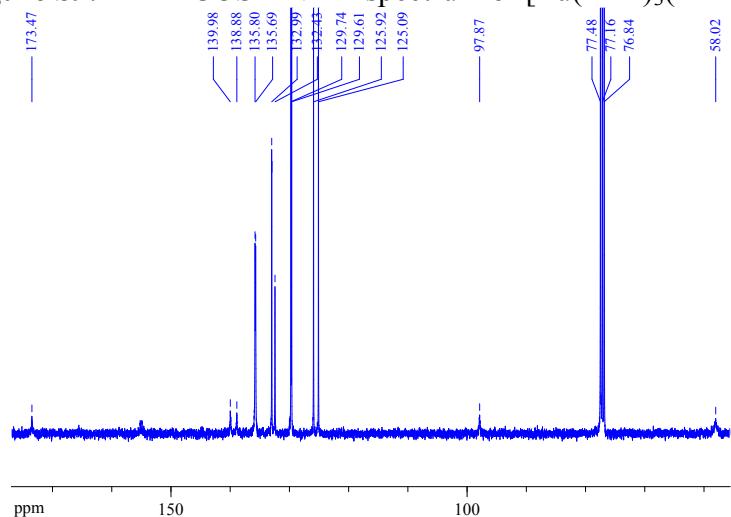
**Figure S7.**  $^1\text{H}$  NMR spectrum of  $[\text{Eu}(\text{TTA})_3(\text{EPHEN})]$



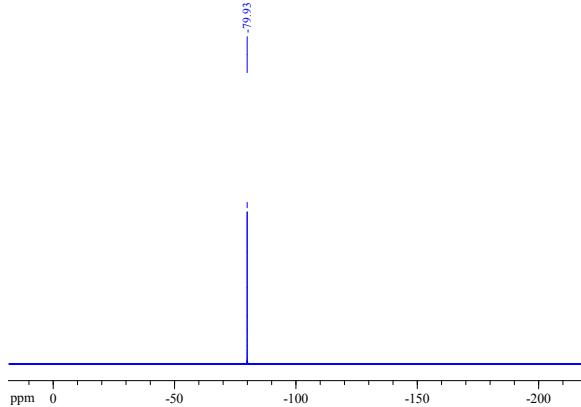
**Figure S8.**  $^1\text{H}$  NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{TPPO})_2]$



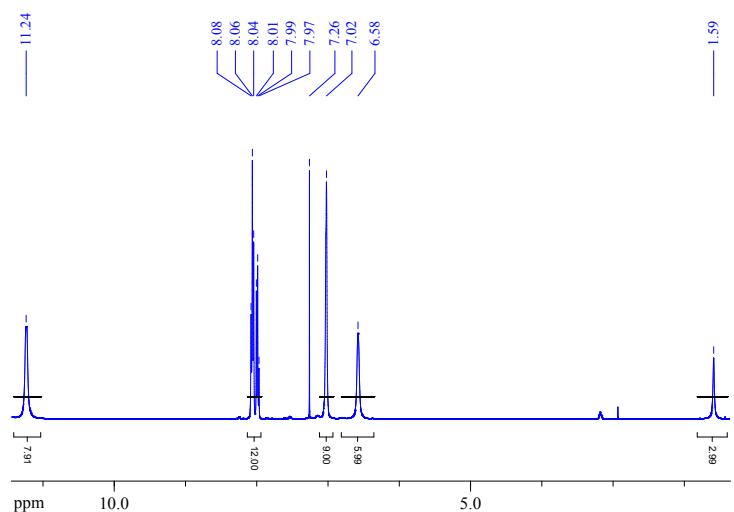
**Figure S9.**  $^1\text{H}$ - $^1\text{H}$  COSY NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{TPPO})_2]$



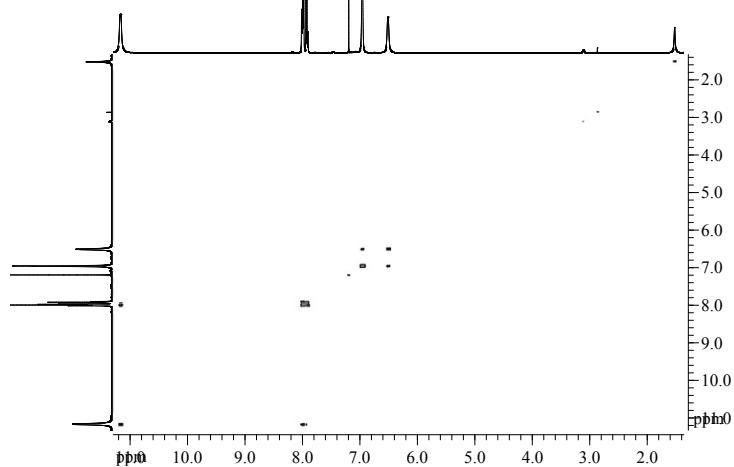
**Figure S10.**  $^{13}\text{C}$  NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{TPPO})_2]$



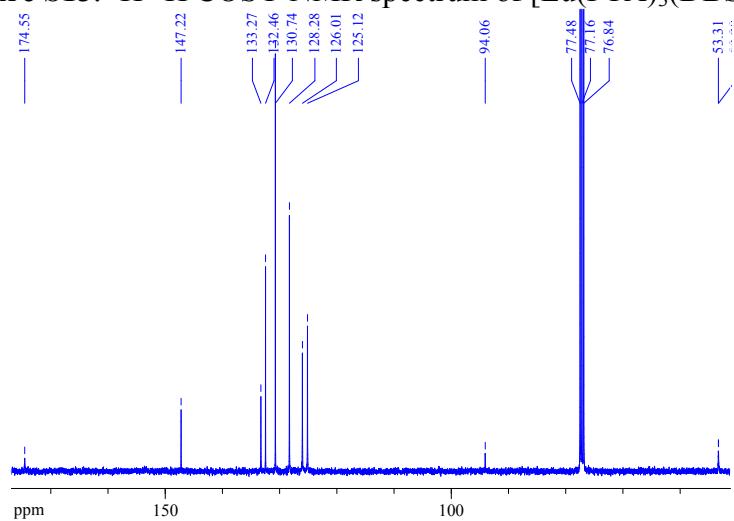
**Figure S11.**  $^{19}\text{F}$  NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{TPPO})_2]$



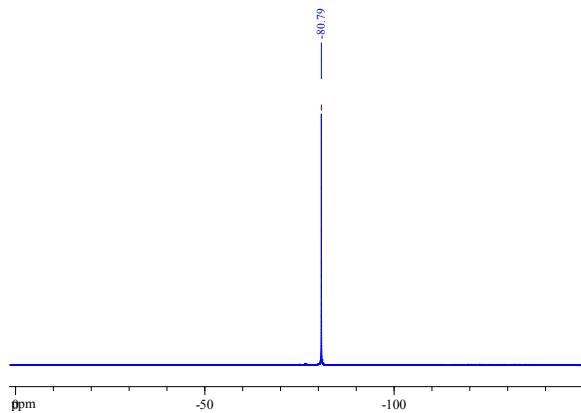
**Figure S12.**  $^1\text{H}$  NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{DBSO})_2]$



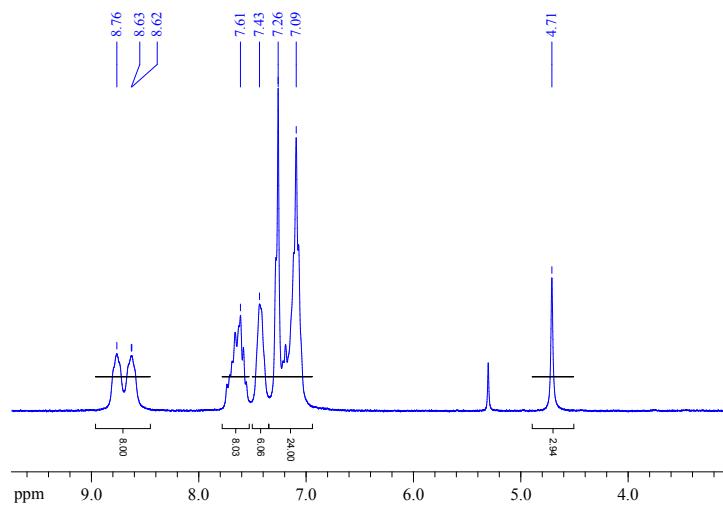
**Figure S13.**  $^1\text{H}$ - $^1\text{H}$  COSY NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{DBSO})_2]$



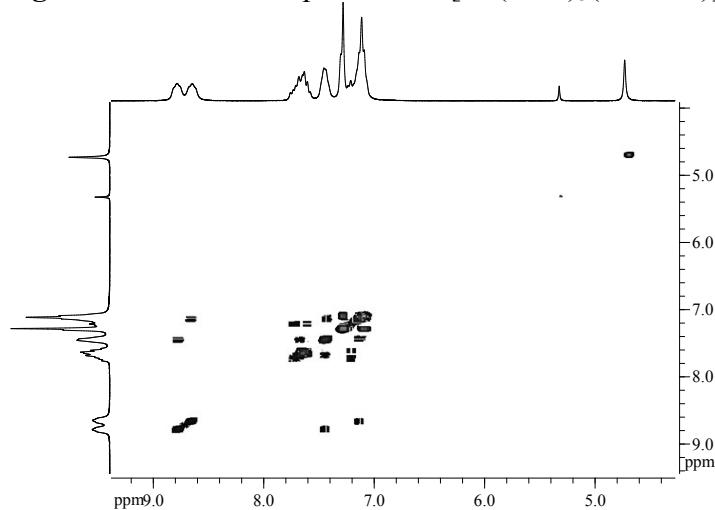
**Figure S14.**  $^{13}\text{C}$  NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{DBSO})_2]$



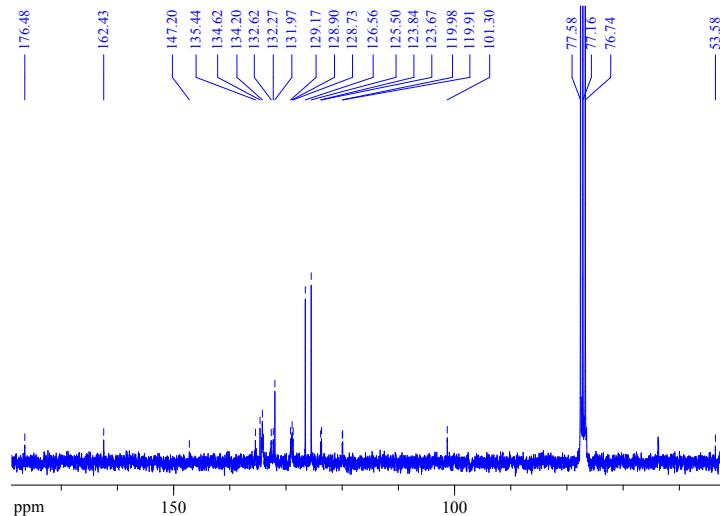
**Figure S15.**  $^{19}\text{F}$  NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{DBSO})_2]$



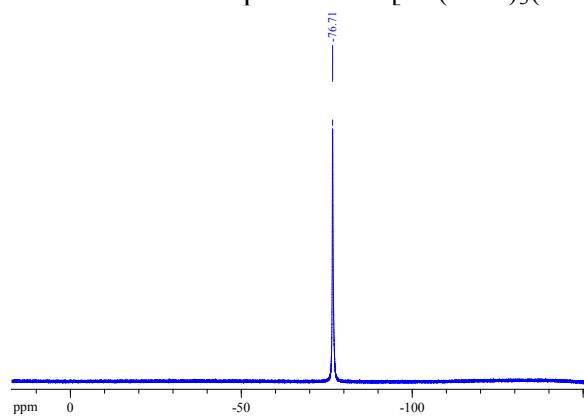
**Figure S16.**  $^1\text{H}$  NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{DPEPO})]$



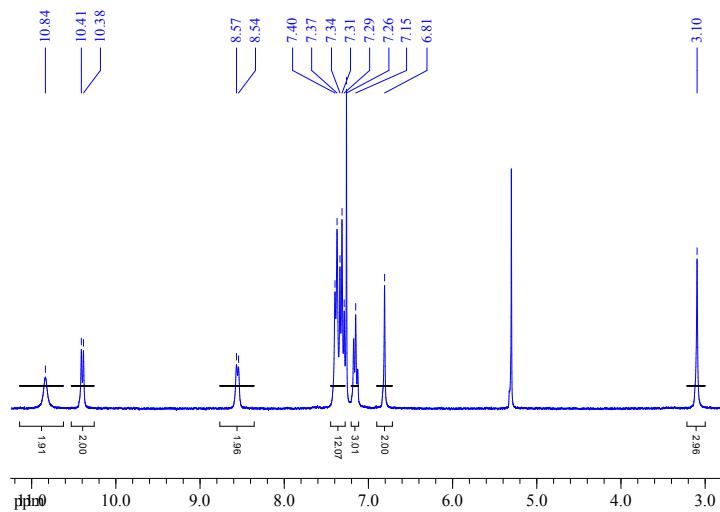
**Figure S17.**  $^1\text{H}-^1\text{H}$  COSY NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{DPEPO})]$



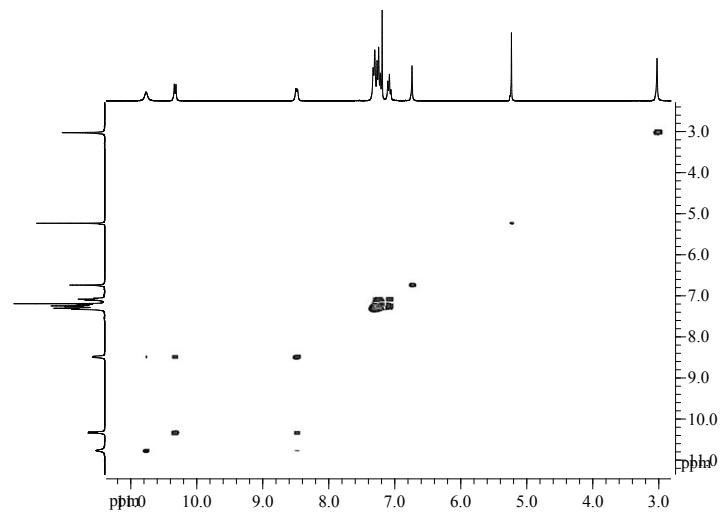
**Figure S18.** <sup>13</sup>C NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{DPEPO})]$



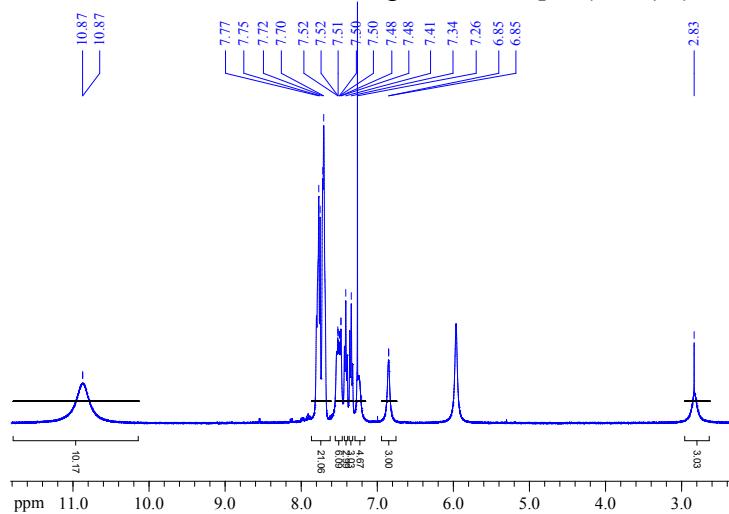
**Figure S19.** <sup>19</sup>F NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{DPEPO})]$



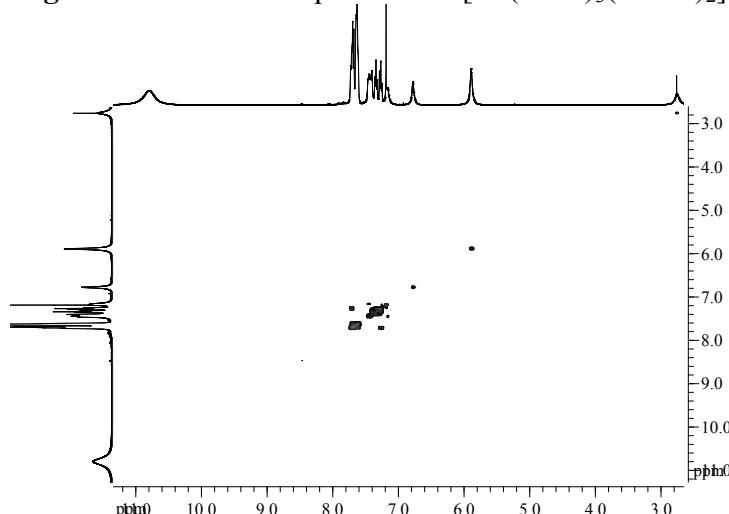
**Figure S20.** <sup>1</sup>H NMR spectrum of  $[\text{Eu}(\text{PTA})_3(\text{EPhen})]$



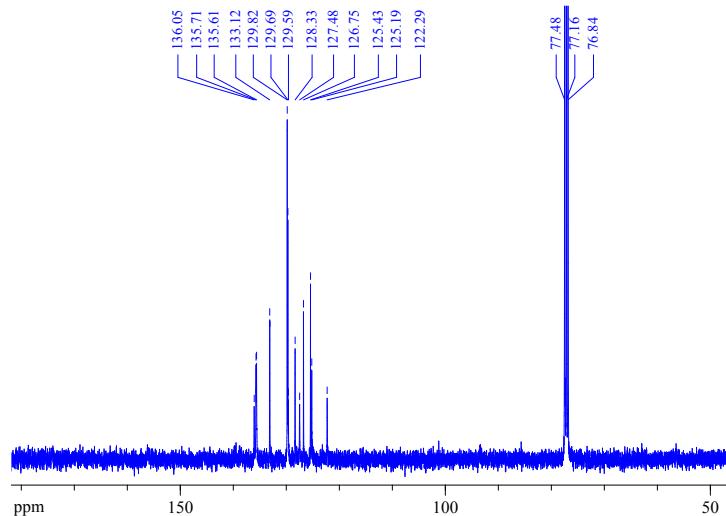
**Figure S21.** <sup>1</sup>H-<sup>1</sup>H COSY NMR spectrum of [Eu(PTA)<sub>3</sub>(EPhen)]



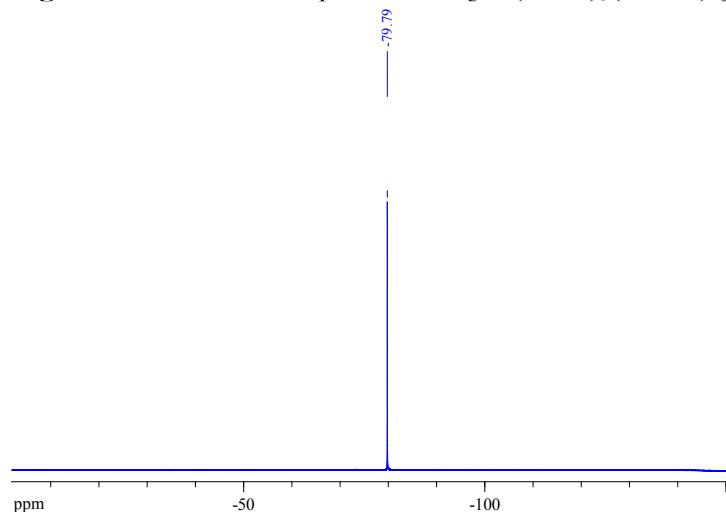
**Figure S22.** <sup>1</sup>H NMR spectrum of [Eu(NTA)<sub>3</sub>(TPPO)<sub>2</sub>]



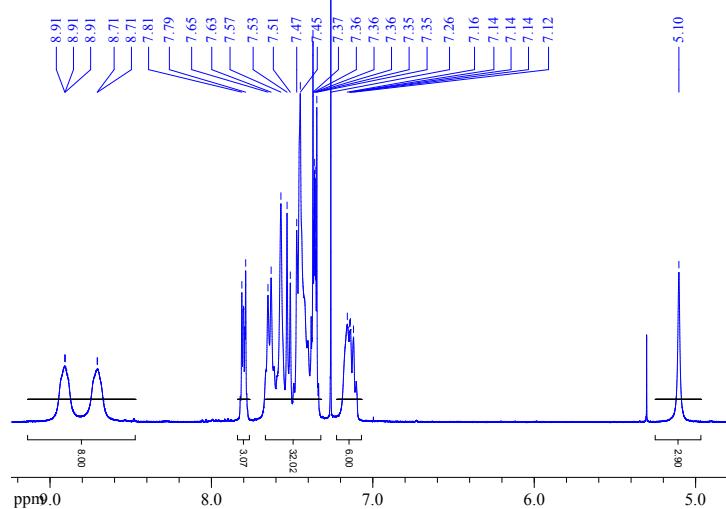
**Figure S23.** <sup>1</sup>H-<sup>1</sup>H COSY NMR spectrum of [Eu(NTA)<sub>3</sub>(TPPO)<sub>2</sub>]



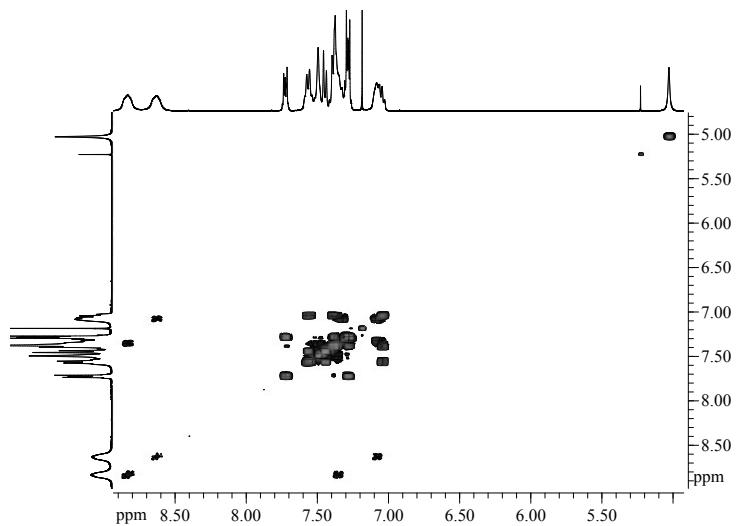
**Figure S24.** <sup>13</sup>C NMR spectrum of [Eu(NTA)<sub>3</sub>(TPPO)<sub>2</sub>]



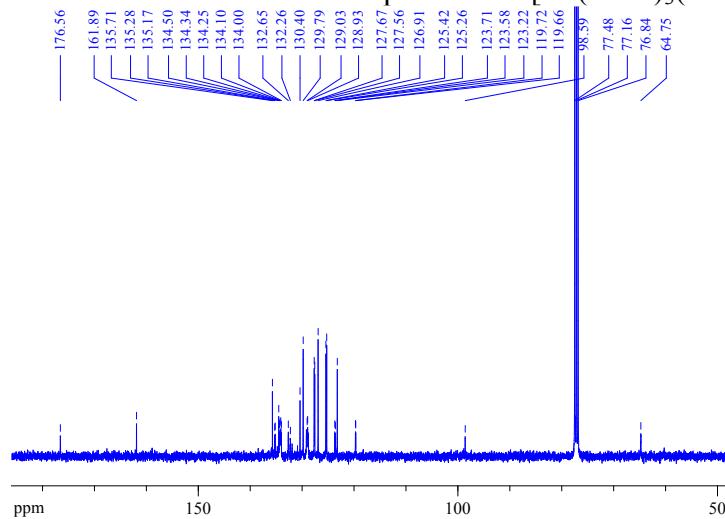
**Figure S25.** <sup>19</sup>F NMR spectrum of [Eu(NTA)<sub>3</sub>(TPPO)<sub>2</sub>]



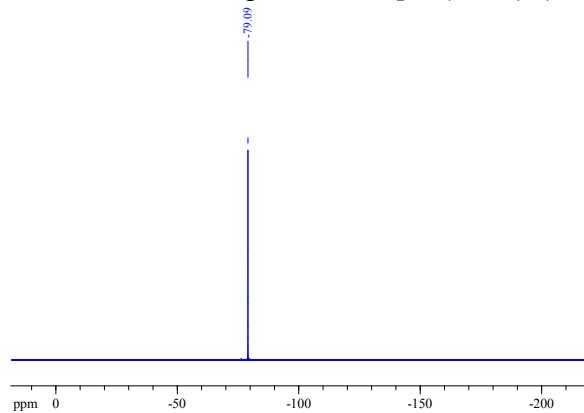
**Figure S26.** <sup>1</sup>H NMR spectrum of [Eu(NTA)<sub>3</sub>(DPEPO)]



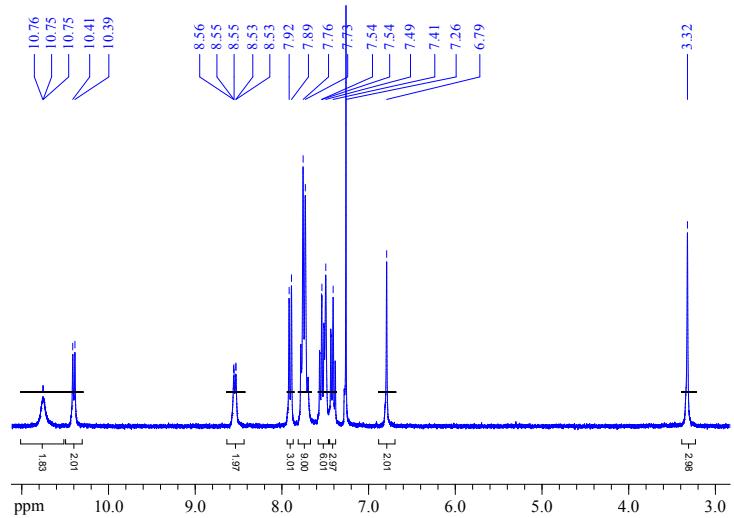
**Figure S27.**  $^1\text{H}$ - $^1\text{H}$  COSY NMR spectrum of  $[\text{Eu}(\text{NTA})_3(\text{TPPO})_2]$



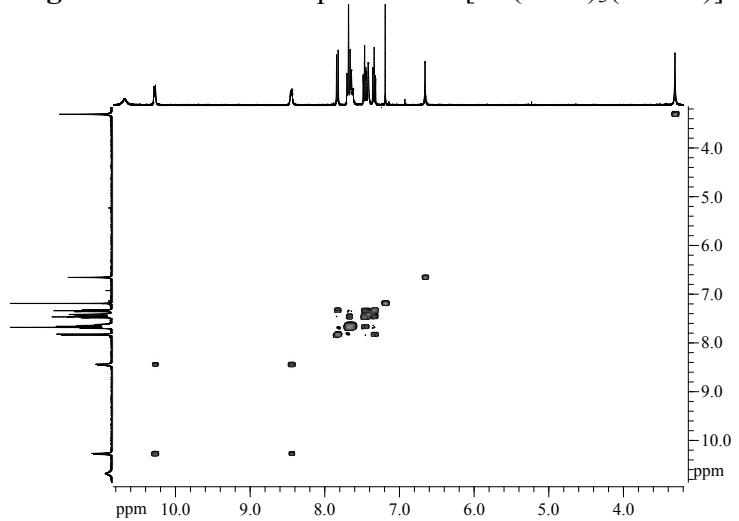
**Figure S28.**  $^{13}\text{C}$  NMR spectrum of  $[\text{Eu}(\text{NTA})_3(\text{TPPO})_2]$



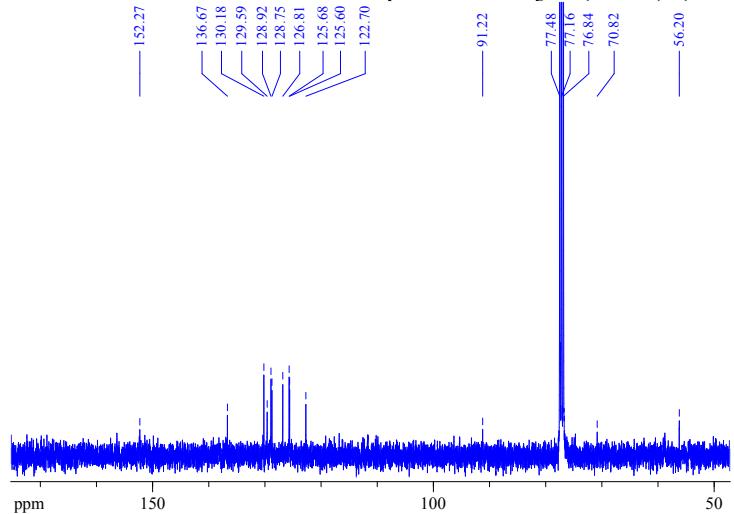
**Figure S29.**  $^{19}\text{F}$  NMR spectrum of  $[\text{Eu}(\text{NTA})_3(\text{TPPO})_2]$



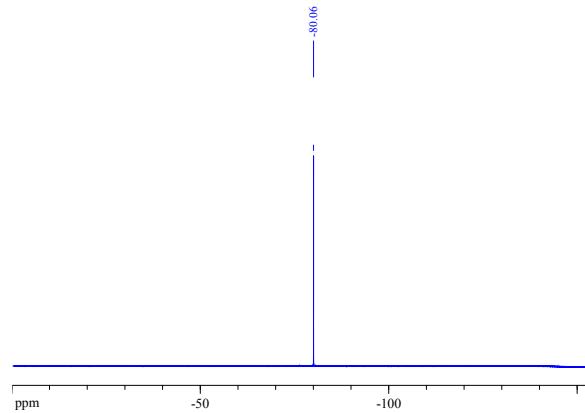
**Figure S30.**  $^1\text{H}$  NMR spectrum of  $[\text{Eu}(\text{NTA})_3(\text{EPhen})]$



**Figure S31.**  $^1\text{H}$ - $^1\text{H}$  COSY NMR spectrum of  $[\text{Eu}(\text{NTA})_3(\text{EPhen})]$

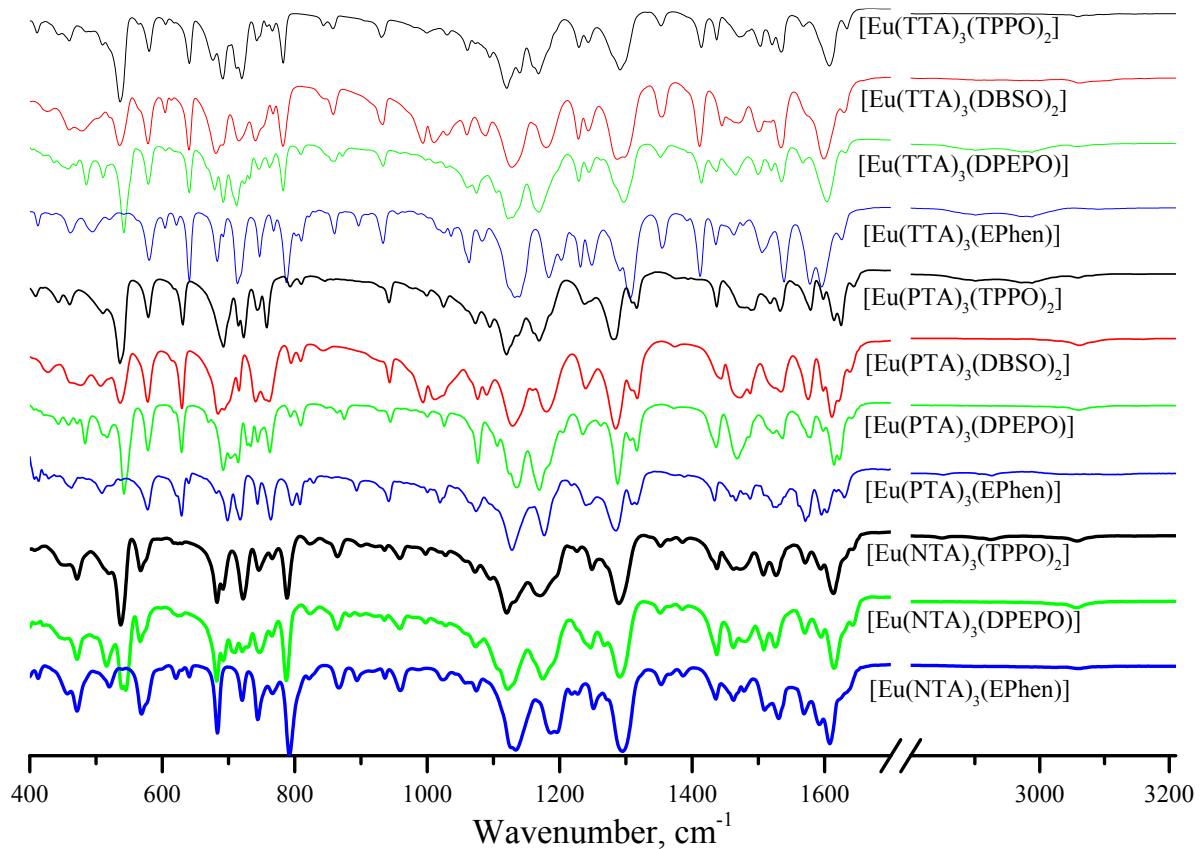


**Figure S32.**  $^{13}\text{C}$  NMR spectrum of  $[\text{Eu}(\text{NTA})_3(\text{EPhen})]$



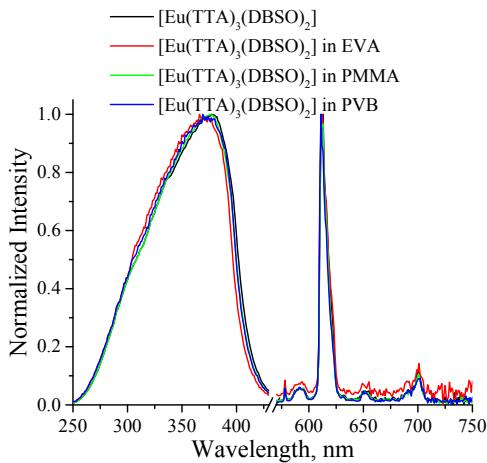
**Figure S33.** <sup>19</sup>F NMR spectrum of  $[\text{Eu}(\text{NTA})_3(\text{EPhen})]$

### Infrared spectroscopy

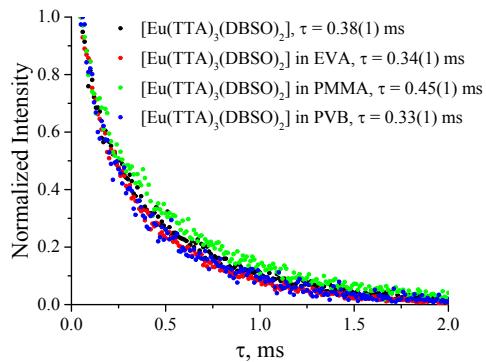


**Figure S34.** IR spectra of europium (III) coordination complexes studied in this work.

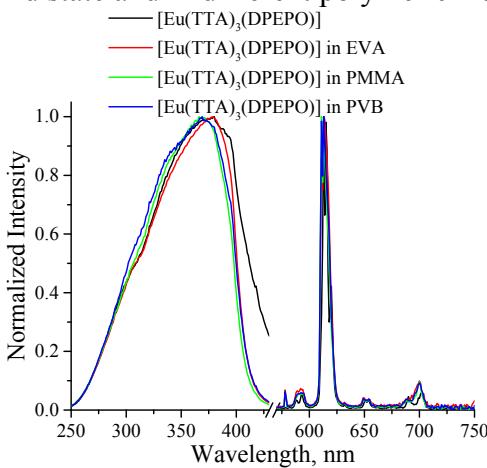
## Photo-physical properties



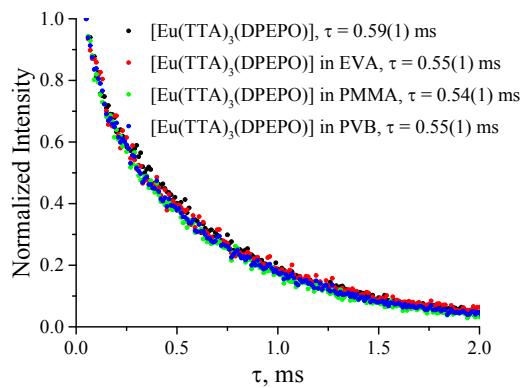
**Figure S35.** Excitation and emission spectra of  $[\text{Eu}(\text{TTA})_3(\text{DBSO})_2]$  in solid state and encapsulated in EVA, PMMA and PVB. The excitation spectra were recorded by monitoring the  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition ( $\lambda_{\text{em}} = 613 \text{ nm}$ ), and for the emission spectra the  $\lambda_{\text{ex}} = 340 \text{ nm}$ .



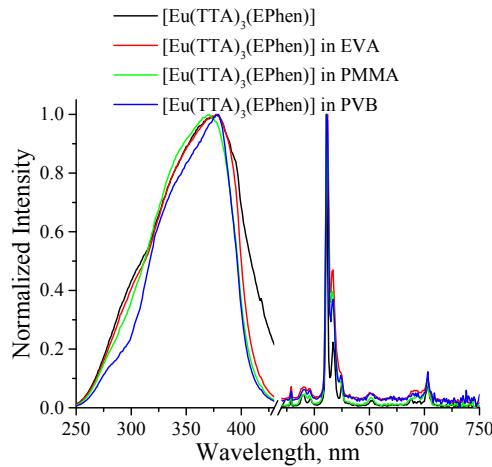
**Figure S36.** Photoluminescence decay ( $\lambda_{\text{em}} = 613 \text{ nm}$ ,  $\lambda_{\text{ex}} = 340 \text{ nm}$ ) of  $[\text{Eu}(\text{TTA})_3(\text{DBSO})_2]$  in solid state and in different polymeric matrices.



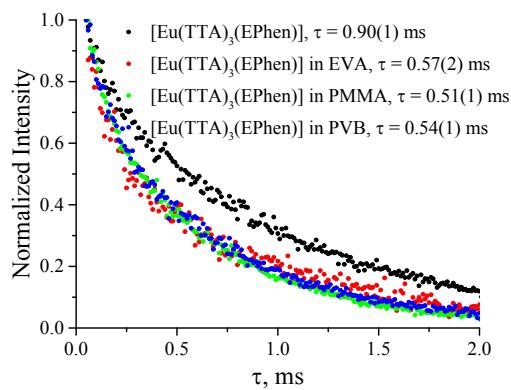
**Figure S37.** Excitation and emission spectra of  $[\text{Eu}(\text{TTA})_3(\text{DPEPO})]$  in solid state and encapsulated in EVA, PMMA and PVB. The excitation spectra were recorded by monitoring the  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition ( $\lambda_{\text{em}} = 613 \text{ nm}$ ), and for the emission spectra the  $\lambda_{\text{ex}} = 340 \text{ nm}$ .



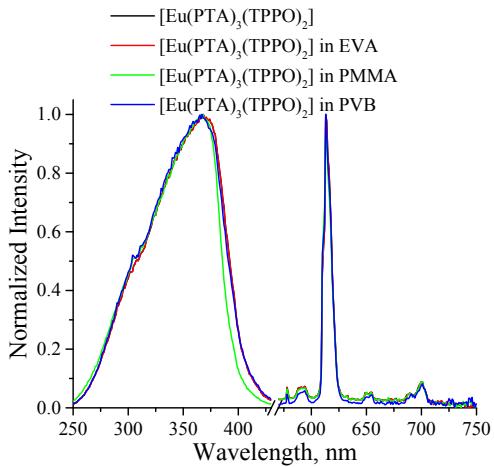
**Figure S38.** Photoluminescence decay ( $\lambda_{\text{em}} = 613$  nm,  $\lambda_{\text{ex}} = 340$  nm) of  $[\text{Eu}(\text{TTA})_3(\text{DPEPO})]$  in solid state and in different polymeric matrices.



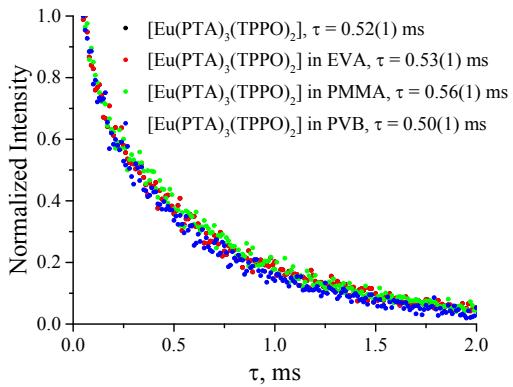
**Figure S39.** Excitation and emission spectra of  $[\text{Eu}(\text{TTA})_3(\text{EPhen})]$  in solid state and encapsulated in EVA, PMMA and PVB. The excitation spectra were recorded by monitoring the  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition ( $\lambda_{\text{em}} = 613$  nm), and for the emission spectra the  $\lambda_{\text{ex}} = 340$  nm.



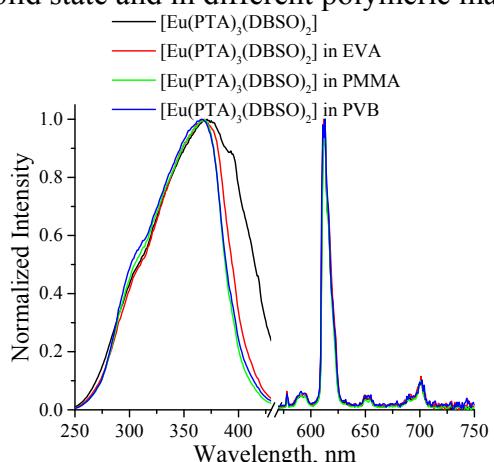
**Figure S40.** Photoluminescence decay ( $\lambda_{\text{em}} = 613$  nm,  $\lambda_{\text{ex}} = 340$  nm) of  $[\text{Eu}(\text{TTA})_3(\text{EPhen})]$  in solid state and in different polymeric matrices.



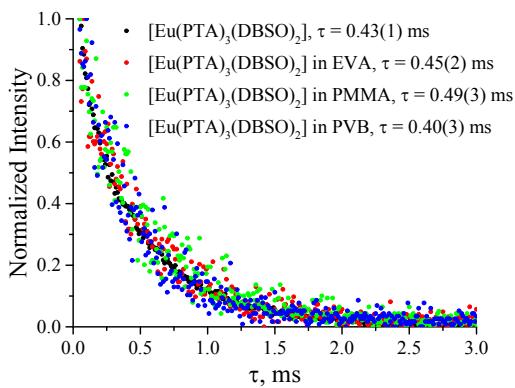
**Figure S41.** Excitation and emission spectra of  $[\text{Eu}(\text{PTA})_3(\text{TPPO})_2]$  in solid state and encapsulated in EVA, PMMA and PVB. The excitation spectra were recorded by monitoring the  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition ( $\lambda_{\text{em}} = 613$  nm), and for the emission spectra the  $\lambda_{\text{ex}} = 340$  nm.



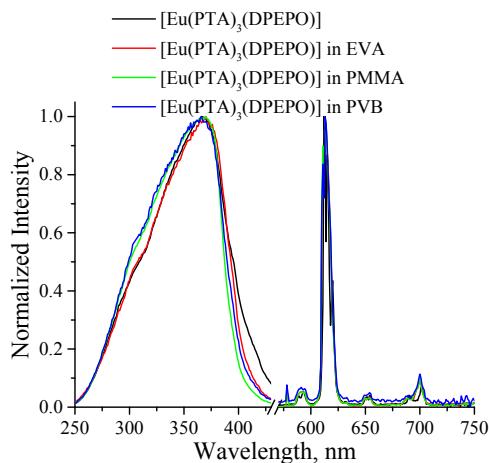
**Figure S42.** Photoluminescence decay ( $\lambda_{\text{em}} = 613$  nm,  $\lambda_{\text{ex}} = 340$  nm) of  $[\text{Eu}(\text{PTA})_3(\text{TPPO})_2]$  in solid state and in different polymeric matrices.



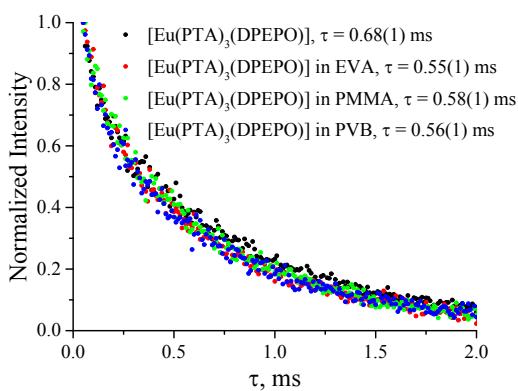
**Figure S43.** Excitation and emission spectra of  $[\text{Eu}(\text{PTA})_3(\text{DBSO})_2]$  in solid state and encapsulated in EVA, PMMA and PVB. The excitation spectra were recorded by monitoring the  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition ( $\lambda_{\text{em}} = 613$  nm), and for the emission spectra the  $\lambda_{\text{ex}} = 340$  nm.



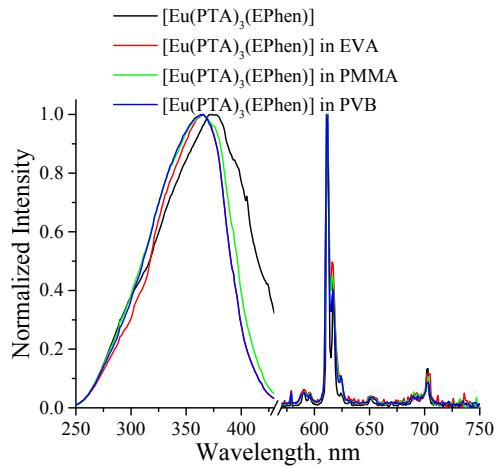
**Figure S44.** Photoluminescence decay ( $\lambda_{\text{em}} = 613$  nm,  $\lambda_{\text{ex}} = 350$  nm) of  $[\text{Eu}(\text{PTA})_3(\text{DBSO})_2]$  in solid state and in different polymeric matrices.



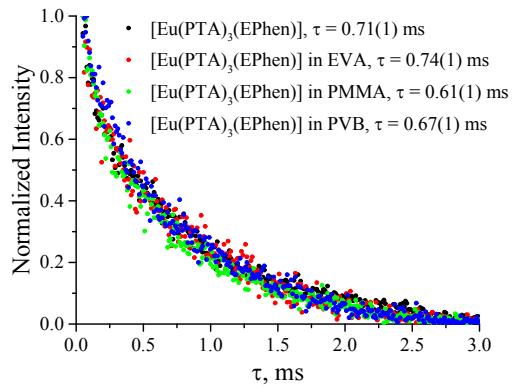
**Figure S45.** Excitation and emission spectra of  $[\text{Eu}(\text{PTA})_3(\text{DPEPO})]$  in solid state and encapsulated in EVA, PMMA and PVB. The excitation spectra were recorded by monitoring the  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition ( $\lambda_{\text{em}} = 613$  nm), and for the emission spectra the  $\lambda_{\text{ex}} = 340$  nm.



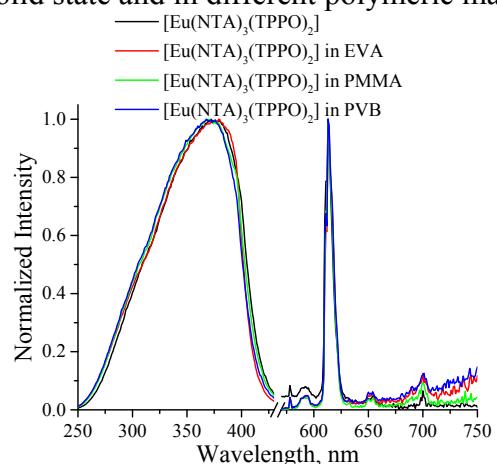
**Figure S46.** Photoluminescence decay ( $\lambda_{\text{em}} = 613$  nm,  $\lambda_{\text{ex}} = 340$  nm) of  $[\text{Eu}(\text{PTA})_3(\text{DPEPO})]$  in solid state and in different polymeric matrices.



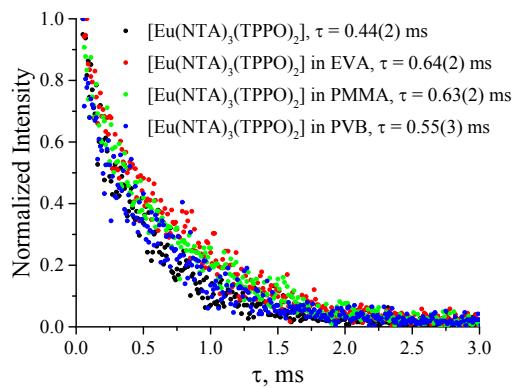
**Figure S47.** Excitation and emission spectra of  $[\text{Eu}(\text{PTA})_3(\text{EPhen})]$  in solid state and encapsulated in EVA, PMMA and PVB. The excitation spectra were recorded by monitoring the  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition ( $\lambda_{\text{em}} = 613$  nm), and for the emission spectra the  $\lambda_{\text{ex}} = 340$  nm.



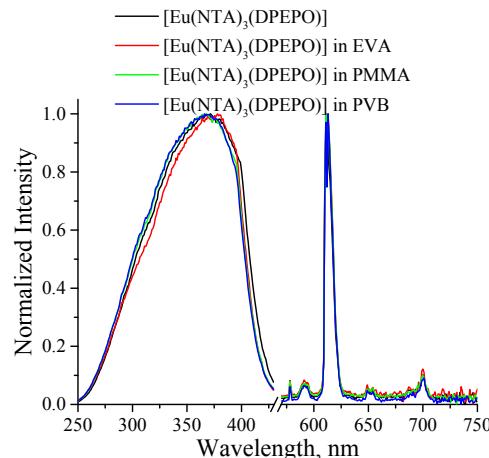
**Figure S48.** Photoluminescence decay ( $\lambda_{\text{em}} = 613$  nm,  $\lambda_{\text{ex}} = 340$  nm) of  $[\text{Eu}(\text{PTA})_3(\text{EPhen})]$  in solid state and in different polymeric matrices.



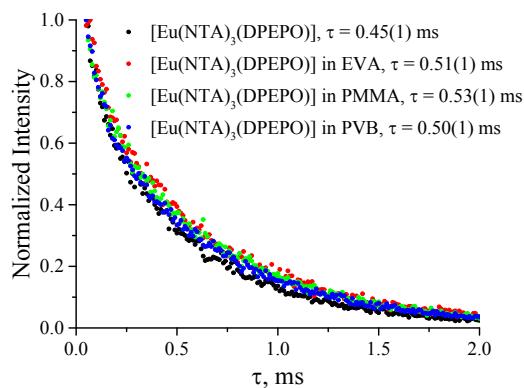
**Figure S49.** Excitation and emission spectra of  $[\text{Eu}(\text{NTA})_3(\text{TPPO})_2]$  in solid state and encapsulated in EVA, PMMA and PVB. The excitation spectra were recorded by monitoring the  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition ( $\lambda_{\text{em}} = 613$  nm), and for the emission spectra the  $\lambda_{\text{ex}} = 340$  nm.



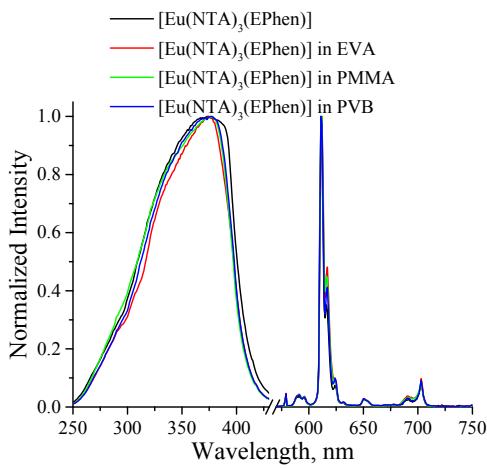
**Figure S50.** Photoluminescence decay ( $\lambda_{\text{em}} = 613$  nm,  $\lambda_{\text{ex}} = 340$  nm) of  $[\text{Eu}(\text{NTA})_3(\text{TPPO})_2]$  in solid state and in different polymeric matrices.



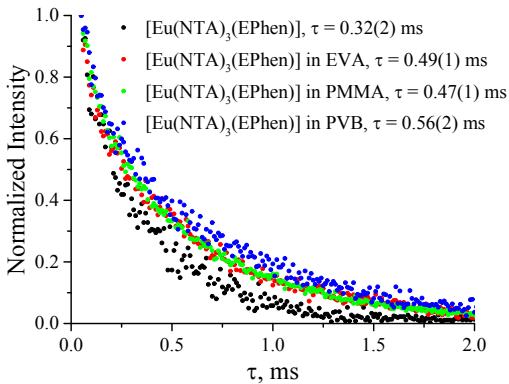
**Figure S51.** Excitation and emission spectra of  $[\text{Eu}(\text{NTA})_3(\text{DPEPO})]$  in solid state and encapsulated in EVA, PMMA and PVB. The excitation spectra were recorded by monitoring the  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition ( $\lambda_{\text{em}} = 613$  nm), and for the emission spectra the  $\lambda_{\text{ex}} = 340$  nm.



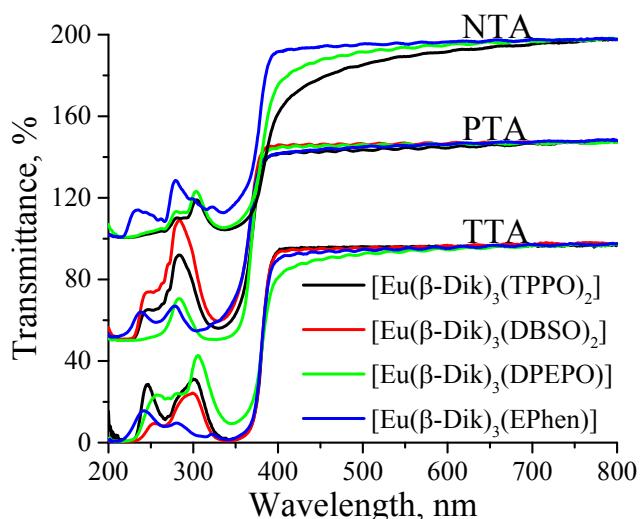
**Figure S52.** Photoluminescence decay ( $\lambda_{\text{em}} = 613$  nm,  $\lambda_{\text{ex}} = 340$  nm) of  $[\text{Eu}(\text{NTA})_3(\text{DPEPO})]$  in solid state and in different polymeric matrices.



**Figure S53.** Excitation and emission spectra of  $[\text{Eu}(\text{NTA})_3(\text{EPhen})]$  in solid state and encapsulated in EVA, PMMA and PVB. The excitation spectra were recorded by monitoring the  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition ( $\lambda_{\text{em}} = 613 \text{ nm}$ ), and for the emission spectra the  $\lambda_{\text{ex}} = 340 \text{ nm}$ .

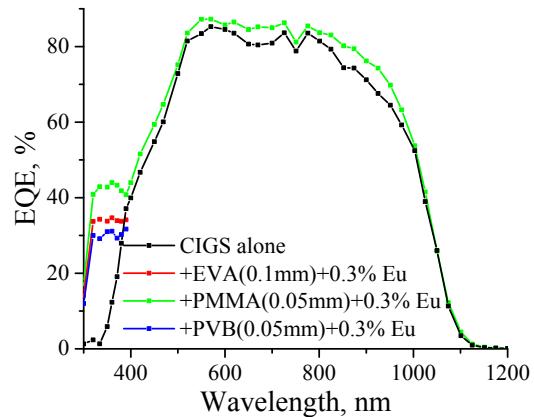


**Figure S54.** Photoluminescence decay ( $\lambda_{\text{em}} = 613 \text{ nm}$ ,  $\lambda_{\text{ex}} = 340 \text{ nm}$ ) of  $[\text{Eu}(\text{NTA})_3(\text{EPhen})]$  in solid state and in different polymeric matrices.

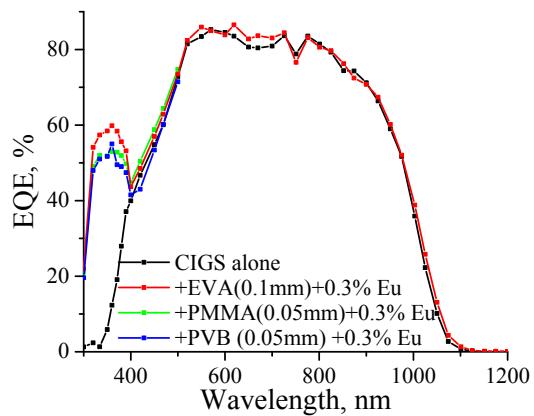


**Figure S55.** Transmittance spectra of europium (III) complexes embedded into EVA.

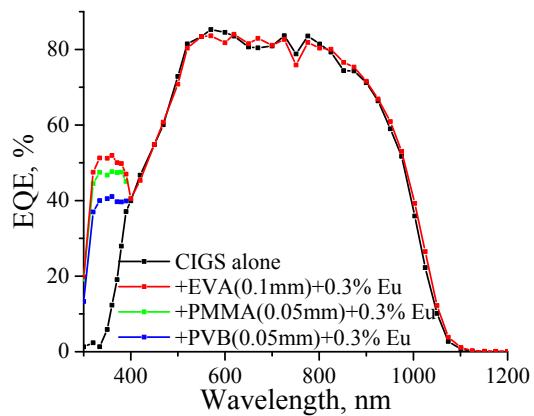
## Spectral response



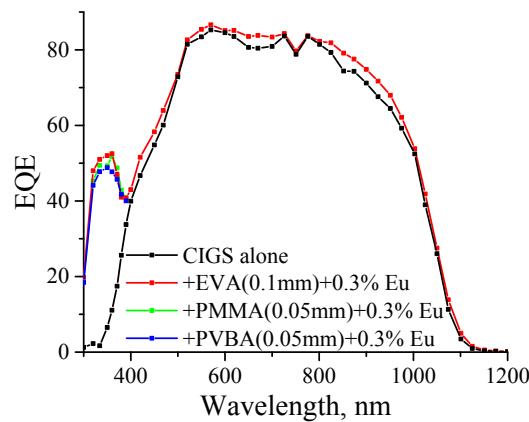
**Figure S56.** EQE spectra of CIGS solar cells encapsulated by different polymers doped with  $[\text{Eu}(\text{TTA})_3(\text{DBSO})_2]$ .



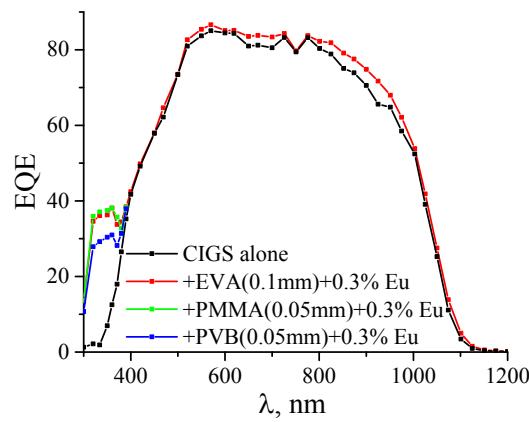
**Figure S57.** EQE spectra of CIGS solar cells encapsulated by different polymers doped with  $[\text{Eu}(\text{TTA})_3(\text{DPEPO})]$ .



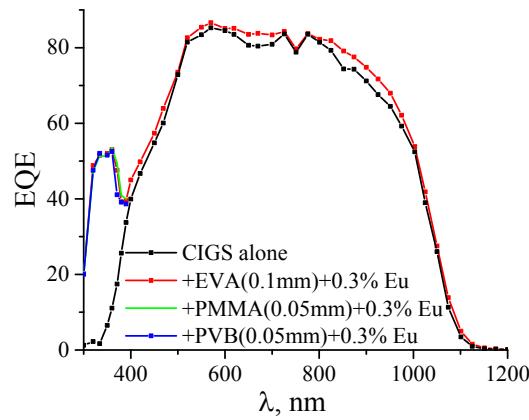
**Figure S58.** EQE spectra of CIGS solar cells encapsulated by different polymers doped with  $[\text{Eu}(\text{TTA})_3(\text{EPhen})]$ .



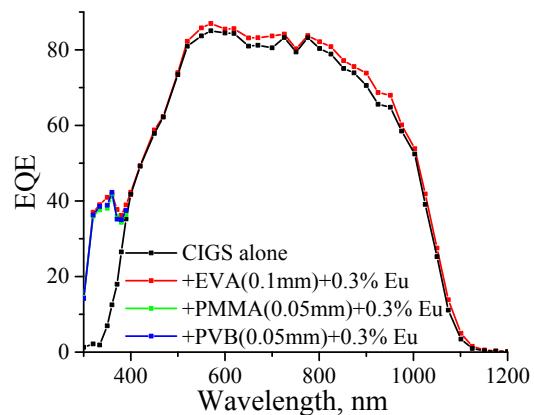
**Figure S59.** EQE spectra of CIGS solar cells encapsulated by different polymers doped with  $[\text{Eu}(\text{PTA})_3(\text{TPPO})_2]$ .



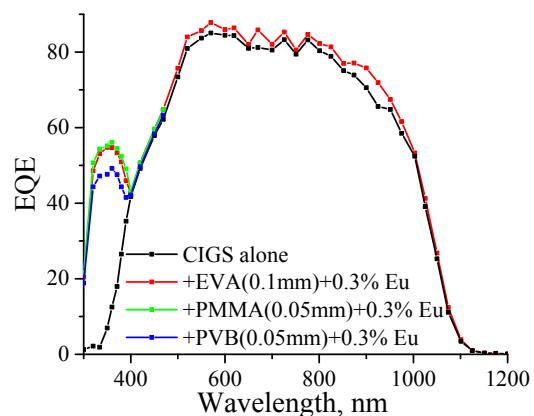
**Figure S60.** EQE spectra of CIGS solar cells encapsulated by different polymers doped with  $[\text{Eu}(\text{PTA})_3(\text{DBSO})_2]$ .



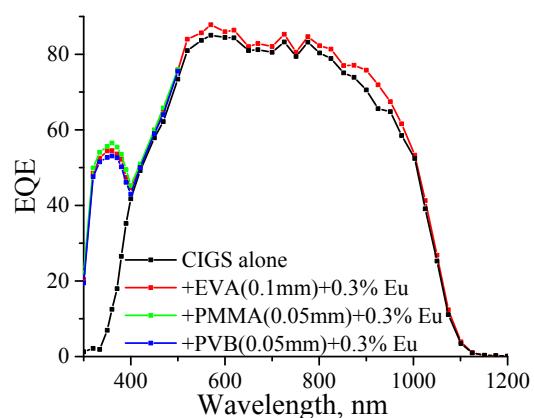
**Figure S61.** EQE spectra of CIGS solar cells encapsulated by different polymers doped with  $[\text{Eu}(\text{PTA})_3(\text{DPEPO})]$ .



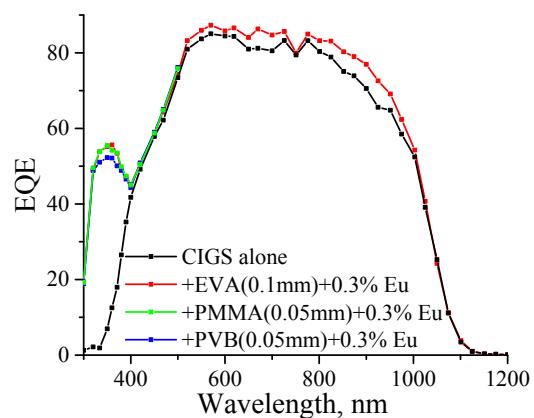
**Figure S62.** EQE spectra of CIGS solar cells encapsulated by different polymers doped with  $[\text{Eu}(\text{PTA})_3(\text{EPhen})]$ .



**Figure S63.** EQE spectra of CIGS solar cells encapsulated by different polymers doped with  $[\text{Eu}(\text{NTA})_3(\text{TPPO})_2]$ .



**Figure S64.** EQE spectra of CIGS solar cells encapsulated by different polymers doped with  $[\text{Eu}(\text{NTA})_3(\text{DPEPO})]$ .



**Figure S65.** EQE spectra of CIGS solar cells encapsulated by different polymers doped with  $[\text{Eu}(\text{NTA})_3(\text{EPhen})]$ .