also clearly illustrated in the field distribution plots shown in Figs. 3(b) and 3(c). Unlike the case of DBR, broadband absorption is always present in metal reflectors due to strong material absorption, manifested as the absorption background in Fig. 3. This broadband absorption accounts for the inferior performance of metal mirrors compared to DBR as we will discussed next.

Figure 4 plots photo current enhancement similar to that shown in Fig. 2 when a spacer layer is inserted between metal reflector and solar cell. The Si cell configuration shown in Fig. 4 is identical to that presented in Fig. 2 except that the DBR is replaced with a planar aluminum reflector. As the spacer layer thickness increases, photo current $J_{ph}$ in the wavelength regime of 750 to 900 nm monotonically increases by 33% from 2.7 mA/cm$^2$ to 3.6 mA/cm$^2$. It is worth noting that the spacer layer thickness should be optimized to minimize optical absorption loss associated with Fabry-Perot resonant modes formed between the grating and reflector as the spacer thickness increases in addition to the guided mode absorption loss. The maximized photo current density (3.6 mA/cm$^2$) in Fig. 4 is still lower than that of the optimal design presented in Fig. 2 where DBR is used instead of metal mirrors. This observation indicates the inferior performance of real metal (in this case, aluminum) compared to DBR due to the strong optical absorption in metals. Lastly, we note that lossless/perfect DBR gives identical photo current density (3.83 mA/cm$^2$) to from the case of a perfect metal reflector, which suggests that DBR can indeed serve as a perfect omnidirectional broadband reflector for photovoltaic light trapping.

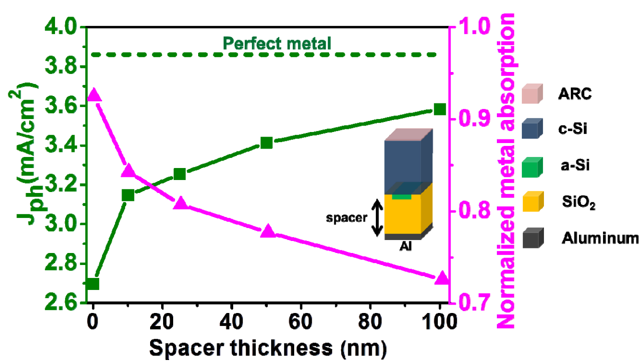


Fig. 4. Influence of spacer layer thickness on integrated photon current (in the wavelength range of 750 nm to 900 nm, green line) and aluminum absorption (magenta line) in the thin c-Si cell structure schematically shown in the inset.

## 4. Conclusions

In conclusion, we identified phased-matched coupling into guided (super) modes and surface plasmon polariton modes to be key loss contributors in backside dielectric or metal reflectors integrated with diffractive gratings. A spacer design is implemented to minimize excitation of the guided modes and thereby mitigate such parasitic optical loss. While the spacer design is applicable to both dielectric DBR and metal reflectors, we show that DBR exhibits superior light trapping performance given its low inherent material absorption, making it a preferred solution for efficient photovoltaic light trapping provided that a cost-effective multi-layer deposition method can be implemented. Last but not least, while our discussion in this paper focuses on 1-D gratings, the spacer design is also applicable to 2-D gratings, which provide significant light trapping enhancement for both polarizations.

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