







## 5.1 Noise analysis

The dominant sources of noise are the photon shot noise, transistor  $M_{pu}$  drain current noise, and the shot and flicker noise of the junction leakage of switch  $M_{sw1}$ . Likely also important, but not considered here, is  $1/f$  noise in  $M_{pu}$ . Considering only the “fast” shot noise, the total input referred contrast noise in  $A_i$  can be computed by treating both  $M_{pu}$  and PD as shot noise sources with power spectral density (PSD) of  $S_f(I) = 2qI_{bg}$  [6, 7]. Summing these two noise current sources at  $V_p$ , dividing by  $g_p^2$  to obtain the  $V_p$  PSD, and integrating over  $V_p$ 's first order lowpass spectrum with cutoff frequency  $f_p = I_{bg}/2\pi A_p C U_T$ , we obtain the total input-referred noise power as

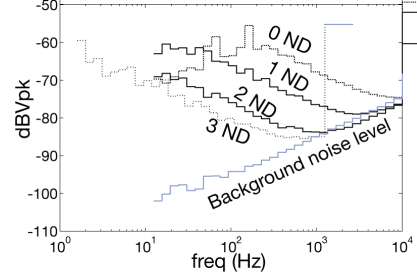
$$\sigma_{\Delta I/I_{bg}}^2 = \frac{q}{A_p C U_T} \quad (5)$$

where  $q$  is the electron charge,  $A_p$  is the gain defined in Eq. (4),  $C$  is the  $V_p$  node capacitance, and  $U_T$  is the thermal voltage. This result is expected as a direct result of the gain-bandwidth tradeoff. In [7], we showed that a “unity gain” source follower photoreceptor with  $A_p = 1$  has input-referred contrast noise of  $q/CU_T$ ; here the gain is  $A_p$  times higher and thus the bandwidth is  $A_p$  times smaller. The total noise is constant and is spread over a bandwidth proportional to intensity, as seen in direct measurements of the PSD of  $V_p$  (Fig. 8).

Using measured and estimated circuit parameters  $A_p \approx 134$  and  $C \approx 110$  fF, we obtain from Eq. (5)  $\sigma_{\Delta I/I_{bg}} \approx 0.07\%$ , substantially lower than our measured minimum event threshold of 0.3%. Our measurement is based on event detection with high reliability, which would imply some multiple of the 1-sigma noise estimate of Eq. (5). However, from (5), we can also obtain the  $V_p$  output noise as  $\sigma_{V_p}^2 = qA_p U_T / C \cong (2.2 \text{ mV})^2$  which accords with measurements of  $\sigma_{V_p} = 2 \text{ mV}$ . The measured  $\sigma_V$  is also fairly independent of illumination; over 3 decades it changes from 2 mV down to 1.7 mV. Therefore we conclude that other noise sources such as  $1/f$  noise or power supply coupling limit our contrast sensitivity.

## 6. DISCUSSION

Although the new pixel increases DVS pixel sensitivity by about a factor of 50 (to 0.3% from 15%), a limitation of the present design is the long time required to reset the PD node after each event (Fig. 4). This is a direct consequence of the gain-bandwidth tradeoff at  $V_p$ ; the high gain achieved here comes at the expense of bandwidth. Typically the photocurrent is rather small (e.g. 1pA) and after charge injection of  $M_{sw1}$ ,  $V_p$  requires time to settle. This  $RC$  time can be many milliseconds under low illumination, as is often the case in practical scenarios for fluorescence microscopy. During this period, the second



**Fig. 8** Octave band noise spectra of  $V_p$  for various background illumination levels. The number  $X$  of decade neutral density filters is  $X$  ND. The vertical scale is power/octave; it rises for the background flat noise spectrum.

differencing amplifier must be held in reset. If it is not, then new events are generated in response to the settling of  $V_p$ . This same requirement also impacts the dynamic range of the circuit. As the light intensity decreases, the settling time also increases, because the conductance looking into  $V_p$  is proportional to the photocurrent. For an array of pixels, the refractory periods would need to be adjusted to handle the settling requirements of the darkest pixels. Clearly, a faster input stage which uses active transimpedance amplification (holding PD at a virtual ground) combined with reduction of the switch charge injection will improve this pixel design, at the cost of shorter integration time and hence higher shot noise limit.

## 7. ACKNOWLEDGEMENTS

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