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_1 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

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

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 $\sigma^2_{V_p} = qA_p U_T/C \cong (2.2\text{ mV})^2$ which accords with measurements of $\sigma_{V_p} = 2$ mV. The measured σ_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 florescence microscopy. During this period, the second

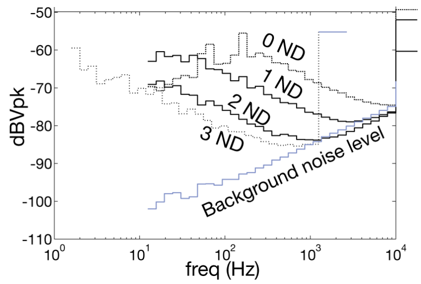

Fig. 8 Octave band noise spectra of V_p for various background illumination levels. The number *X* of decade neutral density filters is *X* ND. The vertical scale is power/octave; it rises for the background flat noise spectrum.

differencing amplifier must be held in reset. If it is not, then new events are generated in response to the settling of Vp. 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 Vp 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.

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