Computer Simulation of Monitoring of Narrow Bandpass Filters at Non-Turning Points

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ABSTRACT

The present work is the result of combining the work reported by Zöller, et al. on the computer simulations of coating processes with monochromatic monitoring with the work reported by Willey on the design and monitoring of narrow bandpass filters at non-turning points. A new software tool which simulates the coating process with monochromatic optical monitoring was introduced which can deal with systematic and random noise/errors of thickness, deposition rate, refractive indices, etc. Narrow bandpass filters have historically been designs of quarter waves at the passband wavelength, and have been monitored at the turning points using the passband wavelength. By direct monitoring at the passband wavelength, errors have been shown to be primarily self compensated, and have allowed much better performance than could otherwise be expected. The turning points are difficult to detect precisely and accurately because the change in transmittance with thickness becomes zero at the desired termination point. The new simulation program is applied here to designs which have been adjusted to have all layer terminations at a distance from turning points in order to gain greater change in the reflectance or transmittance with thickness and thereby reduce layer termination errors. The simulation has allowed the assessment of the merits of the non-turning point monitoring and its limitations as compared to the conventional approach.

INTRODUCTION

A concept was reported by Willey [1] on the design and monitoring of narrow bandpass filters (NBF) at non-turning points, which should offer error reduction potential over the commonly used turning point (TP) monitoring. This has not yet been tested in practice. Zöller, et al. [2] reported on an extensive simulation program to evaluate most of the factors which influence the results of an optical coating production run. Zöller, et al. agreed to use their tool to evaluate the expected behavior and performance of the Willey design and monitoring approach. Willey also independently modified existing simulation software to deal with cases of this new type. The results of the two totally independent evaluations of the approach are compared.

The design approach is to keep the optical thickness of each layer pair in a NBF design at one half wave but to change the relative thickness of the high and low index layers to the overall thickness of the layer pair. A conventional NBF would have equal QWOTs of high and low index to give a ratio of 2:1 between the overall layer pair thickness and the thinnest individual layer. Typically the high index layers were made thinner (but the same could be done with the low index layers instead) to test designs with ratios of 2.67:1, 3.2:1, and 4:1. Figure 1 shows the optical monitoring trace of such a 4:1 design of a three cavity NBF of 42 layers as used in this work. The design of this NBF is: (.5H 1.5L)3 3.632H (1.5L .5H)3 1.345L (.5H 1.5L)3 3.632H (1.5L .5H)3 1.345L (.5H 1.5L)3 3.632H (1.5L .5H)2 1.19989L .96265H .90522L where the substrate is index 1.46 and the H is 2.35 and the L is 1.46 (these indices are used throughout this paper). The high index layers are thin in this case (except the three spacer layers) and the low index layers have two turning points in each layer, but the termination points are NOT at the turning points. The key principle of this approach is to terminate the layers away from the TPs where the noise/error in %T of the termination will cause a smaller error in layer thickness than would occur at a TP termination. The benefits of error compensation are maintained as in conventional NBF monitoring. Larouche, et al.. [3] recently reviewed the TP monitoring approach.

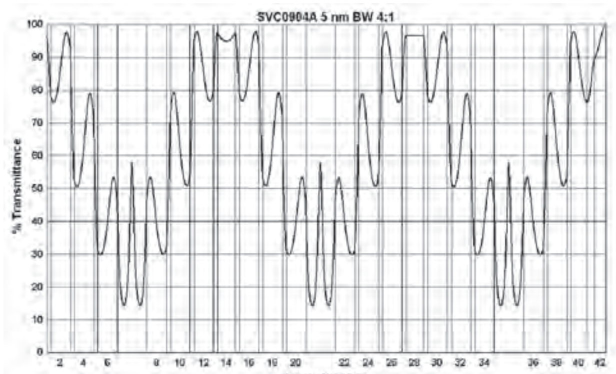

Figure 1: Optical monitoring trace of a 4:1 design for non-turning point layer terminations.

Figure 2 shows the results of 10 simulations of a conventional TP monitored NBF of similar 3-cavity and 42-layer design where the random noise/errors in layer termination were 0.1% transmittance (T). The design of this filter is: (1H 1L)3 4H (1L 1H)3 1L (1H 1L)3 4H (1L 1H)3 1L (1H 1L)3 4H (1L 1H)2

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1L 1.24323H 1.37656L. The last two layers of this design were crystal monitored, but no random errors were added to these last two layers in this case. The layer errors in percent of a QWOT for one case in Figure 2 are shown in Figure 3. The layer noise/errors in Willey's simulations were a random distribution over ±0.1%T; this is somewhat different than the noise/error distribution used by Zöller as stated below. Figure 4 shows the same filter with 0.3%T optical monitoring noise/errors and 1% crystal errors with its corresponding reduction in performance. These results are what is improved by the new approach.

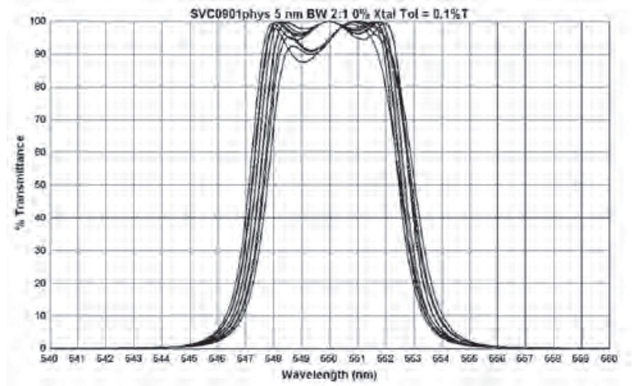

Figure 2: Simulations of 10 runs of the conventional 2:1 NBF design with 0.1%T random noise/errors in TP monitoring and 0% physical monitoring errors.

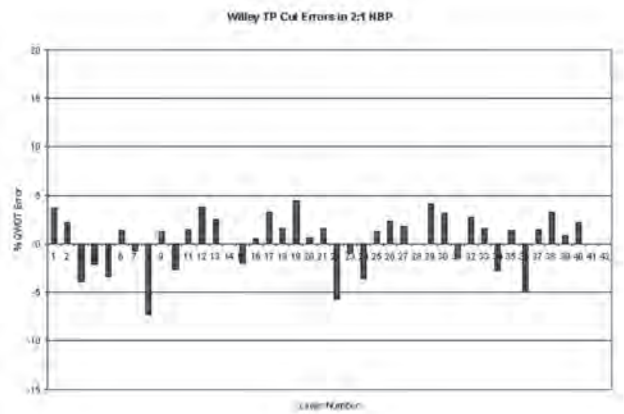

Figure 3: Layer errors in percent of a QWOT at 550 nm on a run of Figure 2. Compare with Figure 12.

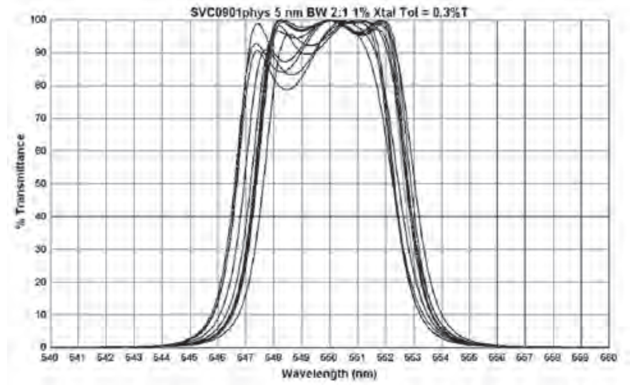

Figure 4: Simulations of same filter as in Figure 2 with 0.3%T optical monitoring noise/errors and 1% physical monitoring errors.

NON-TURNING POINT MONITORING

The distances of the layer termination points from the TPs increase with the layer ratio, and thereby the potential improvement in the termination accuracy. At the lower ratios such as 2.67:1, an accumulation of layer errors can cause a TP to be reached sooner or later than expected. When this happens, the monitoring may breakdown and fail to track properly for the rest of the layers. It is probably possible to make the algorithms capable of dealing also with these problems, but the current software is not yet that sophisticated. When the ratios are larger, more error can be accommodated without causing a breakdown. Figure 5 shows the 2.67:1 ratio case with 0.1%T optical noise/errors and 0% crystal error. One of these simulations has a major breakdown and most of the rest have breakdowns. Figure 6 shows the same design with 0.3%T and 1% crystal errors which give even worse results. It is apparent that a larger ratio than 2.67:1 would be needed for robust results. The design of this NBF is: (.75H 1.25L)3 3.8125H (1.25L .75H)3 1.185L (.75H 1.25L)3 3.8125H (1.25L .75H)3 1.185L (.75H 1.25L)3 3.8125H (1.25L .75H)2 1.25L .48297H .6592L.

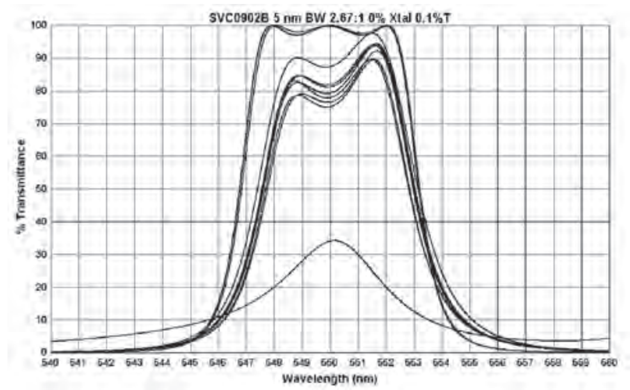

Figure 5: Simulations of 10 runs of the 2.67:1 NBF design with 0.1%T random noise/errors in TP monitoring and 0% physical monitoring errors.

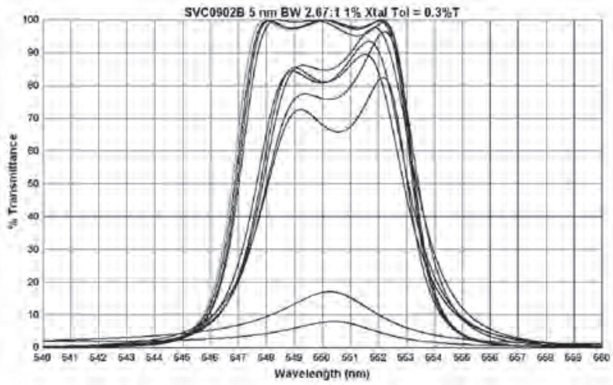

Figure 6: Simulations of 10 runs of the 2.67:1 NBF design with 0.3%T random noise/errors in TP monitoring and 1% physical monitoring errors.

Figure 7 shows that a 3.2:1 ratio would give excellent results for 0.1%T and 0% crystal errors. The design of this filter is: (.625H 1.375L)3 3.7325H (1.375L .625H)3 1.168L (.625H 1.375L)3 3.7325H (1.375L .625H)3 1.168L (.625H 1.375L)3 3.7325H (1.375L .625H)2 1.15334L 1.04597H 1.06385L. Figure 8 shows that 0.3%T and 1% crystal errors would start to give some breakdown. The power of the new approach starts to become more evident in Figure 9 where 0.1%T and no crystal error gives a far better result than the conventional TP monitoring seen in Figure 2 with the same errors. To further illustrate the robustness of the approach, noise/errors of 0.3%T and 3% crystal are seen in Figure 10.

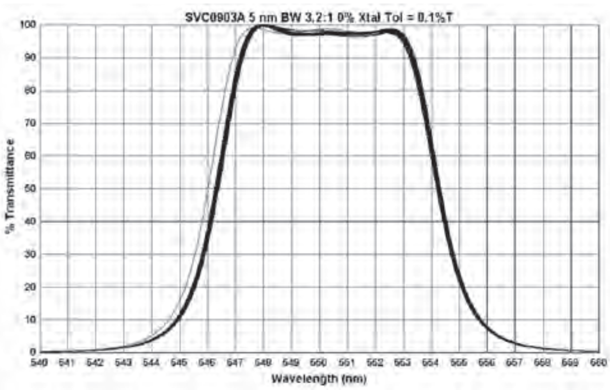

Figure 7: Simulations of 10 runs of the 3.2:1 NBF design with 0.1%T random noise/errors in TP monitoring and 0% physical monitoring errors.

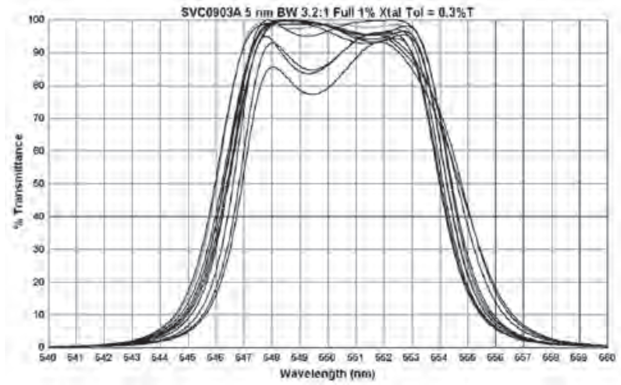

Figure 8: Simulations of 10 runs of the 3.2:1 NBF design with 0.3%T random noise/errors in TP monitoring and 1% physical monitoring errors.

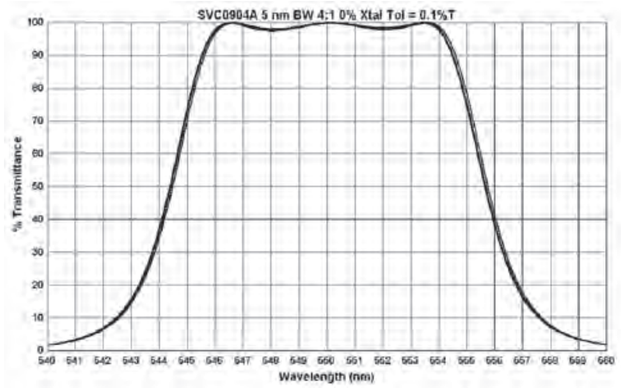

Figure 9: Simulations of 10 runs of the 4:1 NBF design with 0.1%T random noise/errors in TP monitoring and 0% physical monitoring errors.

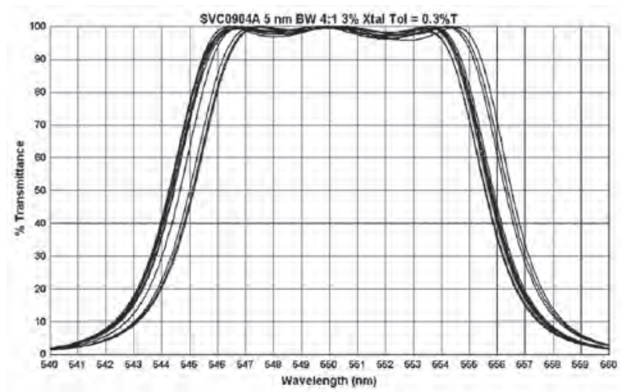

Figure 10: Simulations of 10 runs of the 4:1 NBF design with 0.3%T random noise/errors in TP monitoring and 3% physical monitoring errors.

The thickness of the thinner layers in these designs becomes less with increasing design ratio. This will make the absolute value of the percent thickness errors caused by physical/crystal monitoring to become less with increasing ratios. This adds an advantage to higher ratios also. Here, it is assumed that the percent thickness errors in physical/crystal monitoring are independent of layer thickness, but this may not be a totally valid assumption.

LEYBOLD OPTICS COMPUTER SIMULATIONS

A new software tool, that simulates the coating process with monochromatic optical monitoring using the optical monitor, type OMS 5000 from Leybold Optics, was introduced in Ref. 2. The basic system and the monitoring capabilities of the OMS 5000 were described in Ref. 4.

The simulation tool is communicating with the original OMS 5000 software that is used on the real coating machine. Regarding the optical monitor, therefore the simulation is very close to the real coating process. Process instabilities are described by systematic and random noise/errors of the deposition rates, refractive indices, etc. For the simulation of the monitoring curve, real monochromatic bandwidth, signal noise, measurement frequency, etc., are taken into account. The signal noise is simulated with a Gaussian distribution defined by the standard deviation. This is in contrast to Willey's simulation tool where the noise is simulated with random numbers within a fixed window. Figure 2 versus 11 and Figure 3 versus 12 show how the results differ slightly, but there should be no difficulty in seeing that the two approaches give comparable results in evaluating the monitoring technique.

In addition, the optical monitoring parameters such as signal averaging, monochromatic slit width, and trigger point algorithm, etc. can be specified. Multiple simulated deposition runs can be performed. The simulated monitor curves, the resulting layer thickness errors and the spectra after each layer are recorded and displayed graphically.

The classical 2:1 design of the three-cavity filter was simulated with 1 nm monochromator bandwidth. For clear discrimination of the different designs, a very high noise of the raw monitoring signal was assumed for the simulation. The virtual coating runs were simulated with 0.1% standard deviation. Consequentially the peak-to-peak noise is app. 0.3% - 0.4% with the assumed Gaussian distribution. This is one order of magnitude higher than we normally have in a standard coating chamber.

Besides the noise of the raw signal, the accuracy of the turning point detection depends on the measurement frequency, deposition rate, and the signal processing algorithms. The signal processing software of the OMS 5000 optical monitor uses advanced algorithms for signal averaging and detection of turning points. The degree of averaging can be parameterized.

The optical performance of 10 virtual coating runs with standard parameters for the signal averaging is shown in Figure 11. The coupling layers and the last layer were controlled by quartz crystal with small errors.

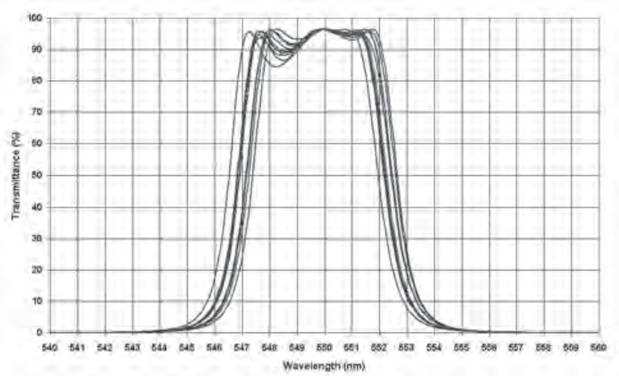

Figure 11: Simulations of 10 runs by Leybold Optics of the conventional 2:1 NBF design with 0.1%T random noise/errors in TP monitoring.

The thickness errors of one of the virtual runs is shown in Figure 12. The thickness errors are up to 15%. It is obvious that self-compensation of thickness errors takes place. Otherwise, the performance would be much worse.

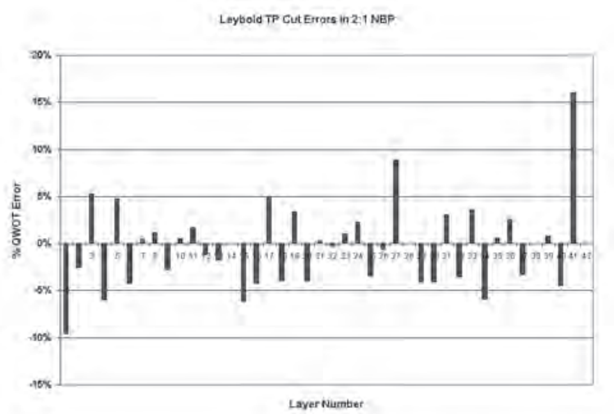

Figure 12: Layer errors in percent of a QWOT at 550 nm on a run of Figure 11. Compare with Figure 3.

In another simulation experiment, a more efficient signal processing was tested for the 2:1 design. Figure 13 shows the results of 10 virtual runs where the signal averaging parameters of the OMS 5000 were better matched to the high signal noise. The raw signal was averaged with higher time constants. This may lead to small overshoots of the turning points of the individual layers. Figure 14 shows the thickness errors of one of these virtual runs. In consideration of the excellent results in comparison to Figures 11 and 12 it is obvious that the overshoots are well corrected by the self compensation.

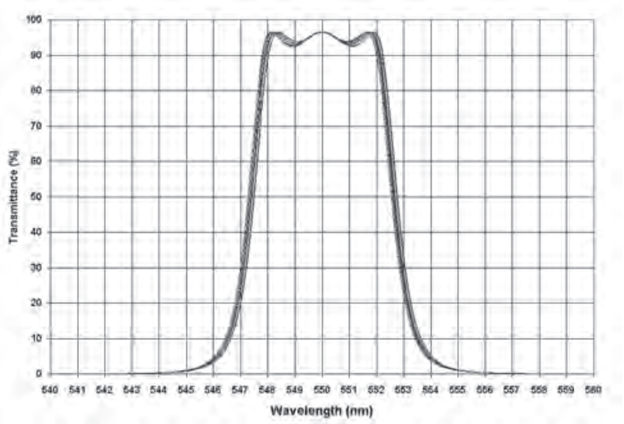

Figure 13: Simulations of 10 runs by Leybold Optics of the conventional 2:1 NBF design with 0.1%T random noise/errors in TP monitoring and a more efficient signal processing.

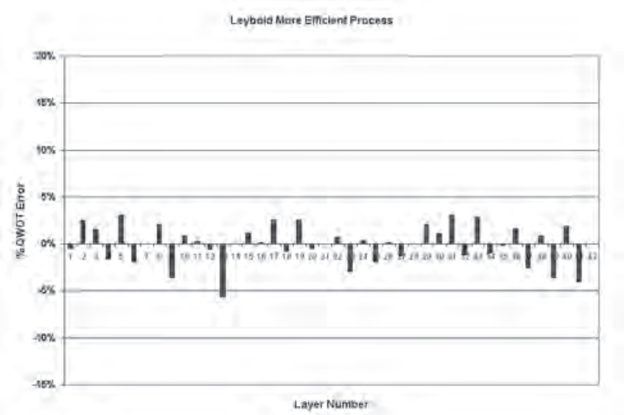

Figure 14: Layer errors in percent of a QWOT at 550 nm on a run of Figure 13.

In addition, the compensation effect in case of refractive index errors was investigated by computer simulation. Figure 15 shows the optical performance of the original 2:1 design in comparison to virtual runs of +1% and -1% error in the refractive index of the H-index material for all H-layers. In this case an ideal monitor signal without noise was assumed. Figure 16 shows the appropriate results for the 4:1 design. In all cases, the self-compensation of refractive index errors works well. Only the bandwidth is effected slightly. The effect of the self-compensation for thickness errors in case of the 3.2:1 and 4:1 designs was already demonstrated above.

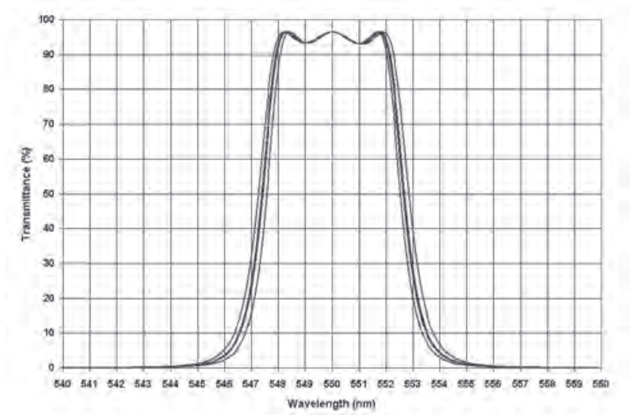

Figure 15: Optical performance of the 2:1 design with ±1% index errors without noise.

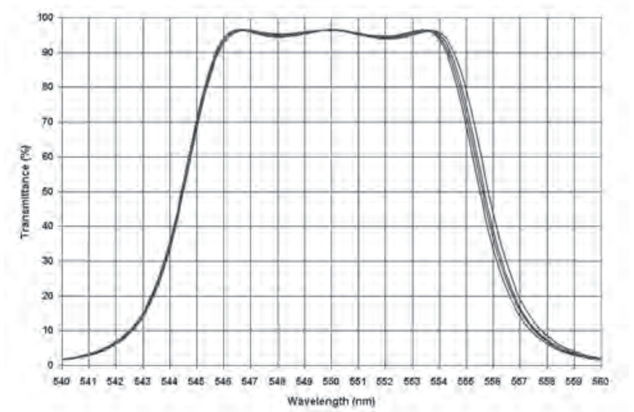

Figure 16: Optical performance of the 4:1 design with ±1% index errors without noise.

DISCUSSION

As pointed out in Ref. 1 and seen in these figures, the bandwidth of the NBF gets wider with increasing ratio. This can be adjusted in the design process if necessary. Reference 1 also shows that the blocking band gets narrower with increasing ratio.

The choice of ratio will be driven to be large enough for robust monitoring, but that needs to be tempered and traded with the blocking bandwidth needed for the NBF in question.

CONCLUSION

Independent simulations have shown that the non-turning point monitoring of NBF can be designed and used to improve the performance of the resulting filters in production.

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