

Microshutters Arrays for the JWST Near Infrared Spectrograph

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ABSTRACT

The Near Infrared Spectrograph (NIRSpec) for the James Webb Space Telescope (JWST) is a multi-object spectrograph operating in the 0.6-5.0 μm spectral range. One of the primary scientific objectives of this instrument is to measure the number and density evolution of galaxies following the epoch of initial formation. NIRSpec is designed to allow simultaneous observation of a large number of sources, vastly increasing the capability of JWST to carry out its objectives. A critical element of the instrument is the programmable field selector, the Microshutter Array. The system consists of four 175 x 384 close packed arrays of individually operable shutters, each element subtending 0.2" x 0.4" on the sky. This device allows simultaneous selection of over 200 candidates for study over the 3.6' x 3.6' field of the NIRSpec, dramatically increasing its efficiency for a wide range of investigations. Here, we describe the development, production, and test of this critical element of the NIRSpec.

Keywords: Microshutter Array, MEMS, JWST, Infrared Spectroscopy, Early Universe, Galaxy Formation

1. INTRODUCTION

We are developing a large format microshutter array for use on the Near Infrared Spectrograph (NIRSpec) on the James Webb Space Telescope (JWST)^{1,2}. It functions as an adaptive input mask for the multi-object instrument. Given an image of an area on the sky, the microshutter array can be programmed to admit light from an ensemble of selected objects, providing a capability for simultaneously observing a large number of discrete objects. The device consists of a two-dimensional array of closely packed slits, each with an independently selectable shutter element. The pattern of shutters to be opened for a given observation is determined by the distribution of objects of interest on the sky and the requirement that their spectra should not overlap on the detector. In cases where there are large numbers of candidate objects in the field, such as the study of high redshift galaxies³, the shutters can be configured to make highly efficient use of nearly the entire detector array, with hundreds of spectra being obtained simultaneously.

A successful aperture mask must provide high transmission efficiency in regions where it is open, excellent blocking in regions where it is closed, and must extend over the 3.6' x 3.6' field of view of the spectrograph. In the design we are developing for JWST, the slits are made on a thin aluminized silicon wafer (Fig. 1). The shutter in each unit cell is a silicon nitride vane metallized with aluminum and overcoated with magnetic stripes. The shutter is supported on a silicon nitride torsion hinge. The shutter is opened by scanning a magnetic across the array, and can be latched electrostatically in the open position. Selection is accomplished by a crosspoint addressing system in which all shutters are released except those required for the particular observation (Fig. 2). Following an observation, the system can be rapidly reconfigured for the next field under study.

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We have demonstrated the required operation and performance for the NIRSpec on prototype arrays. Here we describe the operation and optical performance of the devices, and discuss progress on the final steps in development, the demonstration of required lifetime and the scaling of the prototype arrays to the required format.

2. TECHNICAL APPROACH

In the development of our concept for the field selector for the NIRSpec, there were several important decisions, which defined the path we chose. The most fundamental decision was to produce a device that operated in transmission rather than in reflection as existing micromirror arrays do. There were three motivations for this choice; first, with appropriate baffling, a transmissive microshutter can achieve very high contrast between open and closed state and high transmission in the open state. Second, a transmissive solution could be interchangeable with a mechanical slit alternative, providing an effective backup for the instrument in case of failure in development. Finally, in a reflective system such as with mirrors, the flatness of the reflectors is critical; there is no corresponding requirement for a transmissive system. Adding complexity to the development was the requirement that the microshutter array operate at the low temperature of the NIRSpec, around 37 K.

In order to achieve a high filling factor for an array of shutters on the required scale ($\sim 100 \mu\text{m} \times 200 \mu\text{m}$), silicon micromachining was the obvious choice for the thin walled shutter support structure. Silicon nitride was a good choice for the torsion flexure and shutter vane because of its high strength and resistance to fatigue (Fig. 1). Initial experiments were done with thin silicon, which also worked well, but silicon nitride was ultimately chosen because of its higher strength and lower cost.

Achieving 90° rotation of the shutter on its torsion flexure in a system requiring large fractional open area was a challenging problem. While it could be achieved using electrostatic fields, the very high voltages required presented difficult systems problems. We ultimately chose to deposit a magnetically permeable material on the shutters, and to scan a magnet across the array to open the shutters. A tripole magnetic field is used, so that as it scans across, the shutter experiences a magnetic field which rotates through 180° during the scan, rotating it into contact with the wall of the support frame, where it can be electrostatically captured to the vertical electrode (Fig.2) with a reasonably low voltage.

After configuring the array to the desired configuration (actuation), the shutters are held in the open position by an electrostatic field created by the voltage difference between the shutter vane and the vertical electrode. In the array design, the vertical electrodes are connected to rows, while the shutter vanes are connected to the columns (Fig. 2). During actuation and capture of the shutters, a positive voltage is applied to the shutters, and an equal negative voltage applied to the vertical electrode. The voltages are chosen so that after capture, either the row voltage or the column voltage is sufficient to hold the shutter open. If this is the case, a shutter will only be released if the row voltage and the column voltage are set to zero. In this manner, each shutter in the entire array can be individually released as required. This addressing scheme is particularly appealing, because it requires no active electronic elements on the array; all shutters can be individually controlled using an external crosspoint address scheme.

3. REQUIREMENTS AND DESIGN

The Microshutter Array must meet the scientific and technical requirements set by the NIRSpec instrument (Table 1). Listed here are a subset of key requirements. In this section, we discuss progress in meeting these requirements.

<ul style="list-style-type: none">● Random Access Addressing<ul style="list-style-type: none">— Must allow the opening of any shutter distribution<ul style="list-style-type: none">● > 200 objects simultaneously targeted● Must cover NIRSpec FOV (9 sq. arcmin)● Contrast<ul style="list-style-type: none">— Must have open to closed transmission ratio of >2000 (10,000 goal)● Lifetime<ul style="list-style-type: none">— Must operate for 9.4×10^4 cycles with minimal failures● Must operate in the JWST environment<ul style="list-style-type: none">— $T \sim 37$ K<ul style="list-style-type: none">● Must meet power dissipation requirements (40 mW average at 37 K)— Must fit envelope in NIRSpec instrument— Must meet mass requirements (10 kg)— Radiation - 48 kRad life dose

Table 1. Performance requirements for the Microshutter Array.

3.1. Optical Performance

The basic function of the microshutter array is to block light where it is closed position, and to transmit efficiently where it is open. The NIRSpec instrument requires that this contrast ratio be >2,000 with a goal of 10,000. In order to block light effectively when closed, the shutter vane must be opaque, and leakage around the closed shutter should be limited. The shutter is covered with 2000 Å of aluminum, which is sufficiently opaque to provide adequate blocking. The leakage around the shutter is limited by having a cantilevered light shield that overlaps the metallized shutter vane in the closed position. With proper alignment, any residual leakage is due only to internal reflections and multiple diffraction, allowing the contrast ratio goal of 10,000 to be met.

The transmission efficiency of the array is set by two loss factors, the geometrical blocking of the slit, where only part of the image fits within the slit, and the light which is transmitted through the slit, but is diffracted at angles large enough to miss the subsequent pupil. Both of these losses are also suffered using conventional slits. The shutter's size is selected to be well-matched to the diffraction image of JWST at the long wavelength of the NIRSpec band. The slits have been chosen to be 0.2" in the dispersion direction and 0.4" in cross dispersion. To cover the entire 3.6' x 3.6' field of view of the NIRSpec, we use four arrays in a 175 x 384 format (the 175 shutters are in the cross dispersion direction)(Fig. 4), with permanent fixed slits between the arrays for observations requiring the very highest contrast.

During the 10 year operational life of the NIRSpec, the shutters may be configured as many as 93,000 times. The

microshutter arrays and their actuating mechanism must be reliable over this lifetime, so that at the end of life, no more than 5% of the rows in the microshutter contain permanently open or leaky shutters.

3.2. Mechanical Requirements and design

3.2.1. Magnet transport

The shutters are opened by scanning a tripole magnet across detector array. In the present design, the magnet is 500 μm above the shutter array as it scans across. The scan mechanism must reliably transport the magnet back and forth across the array 93,000 times in the mission lifetime. The average power dissipation must be low, allowing us to meet the requirement of 40 mW time averaged dissipation for the entire cryogenic system. While achieving low power dissipation and long life operation at cryogenic temperatures is challenging, no new techniques are required to produce this mechanism.

3.2.2. Interface and support of microshutter array

The microshutter array must be operable over a wide range of temperatures, from room temperature to its operating temperature of ~ 37 K. One area requiring particular attention is the packaging and mounting of the microshutter array. We have chosen to mount the most challenging component of the system, the microshutter array itself, on a silicon carrier, so this system is as athermal as possible. The support structure and magnet transport stage are made of titanium, so a kinematic mount is required avoid the transmission of internal stresses into the silicon carrier. The required flexures will be machined in the titanium carrier, and the silicon will be bonded to them. The connection between the microshutter carrier and the titanium flexures and any heat straps must perform the thermal function of cooling the device from room temperature and maintaining it at an adequately low operating temperature with the addressing electronic operating.

3.3. Electronic design

The addressing of the microshutter array is accomplished through the control of voltages on the shutter vanes and vertical electrodes. The vertical electrodes are connected in rows on the back side of the wafer, the shutter vanes connected in columns from the front side of the array. Electrical connections from the front side of the microshutter to the carrier are made through indium bumps. Connections from the rows of vertical electrodes to the carrier are made through wire bonds. Each row and column is connected to an output of a 128 bit shift register with high voltage outputs, allowing logical control of all rows and columns for full addressing capability. The warm electronics package must drive the scan motor and provide the proper pattern of voltages on the rows and columns to generate the required patterns of open shutters for each observation.

. The voltages which are required are $\sim \pm 30$ V, so we require high voltage drivers. Initial work has been done using a Supertex HV583 address driver. It works well at room temperature and at the required operating temperature of 37 K, but does not meet the JWST requirement of nominal operation after exposure to 48 kRad of ionizing radiation. A custom chip is being developed to reduce the sensitivity to radiation exposure.

4. TEST RESULTS

The process for shutter fabrication has been under development for about three years, and devices which are now being built can meet many of the requirements for the NIRSpec flight arrays. We will discuss the areas of success, and identify areas that remain to be demonstrated for flight.

4.1. Actuation, Latching, and Addressing

The evaluation of a microshutter must establish; 1) proper electrical function, no shorts or opens. 2) proper mechanical function of shutters. 3) the ability to latch shutters. 4) the ability to deselect shutters and create a desired pattern. The electrical tests are carried out at many steps in the production process, at the completion of processing, and after bonding to the carrier chip. Mechanical function of the shutters is evaluated at the completion of processing prior to mounting by rotating the shutter in a strong magnetic field (the rotisserie facility)(Fig. 3). After mounting on the carrier board, it can

be tested with the tripole magnet, both warm and cold in the comprehensive test cryostat. In this facility, we can also test our ability to latch and to address the shutters (Fig. 4). In general, if shutters can be latched, and there are no shorts or opens in the electrodes, they will be addressable.

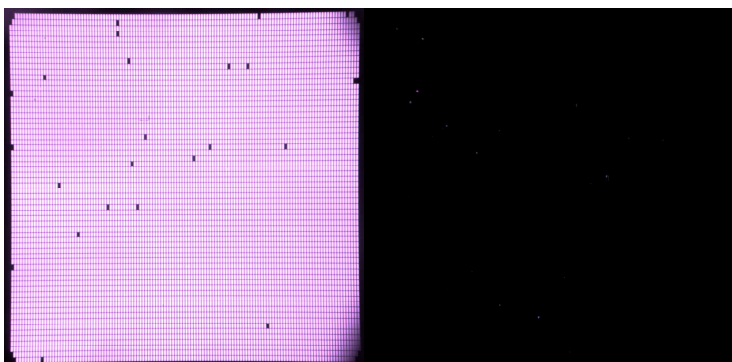


Figure 3. In this mechanical test, the microshutter array is illuminated from the rear. In the frame at the left of the figure, the shutters are opened with a strong large area solenoidal magnetic field. Only about 25 of the 8192 shutters in this prototype fail to open. In the frame on the right, the field is turned off, and the shutters close. In this sample, there are essentially no shutters which remain permanently open at beginning of life. These pictures show that shutters with high pixel yield can be produced.

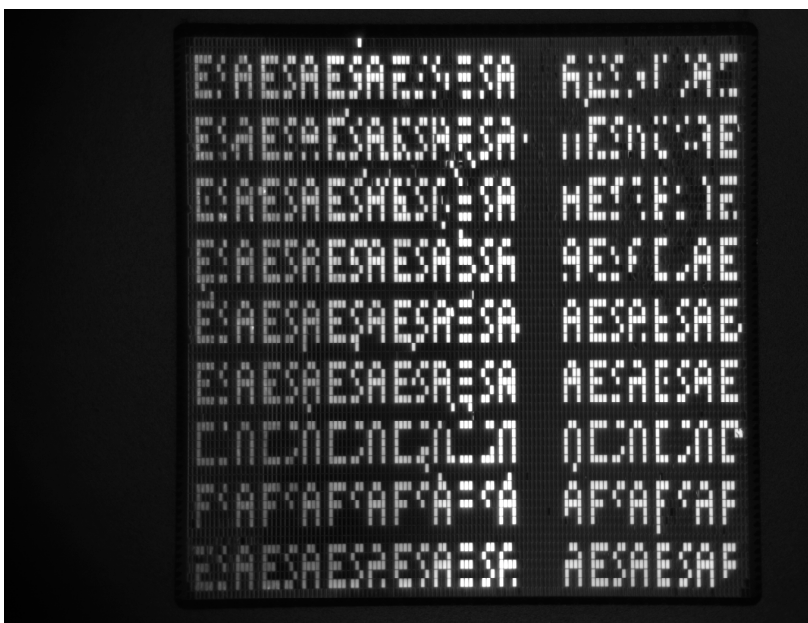


Figure 4. A prototype microshutter array is configured to display a grid of ESAs. The addressing is generally good except for the inactive columns to the right of center, and partial addressability on several rows (due to electrical shorts in this sample). This array is >95% operable mechanically, so in this case, most observed imperfections are due to electrical problems rather than mechanical ones.

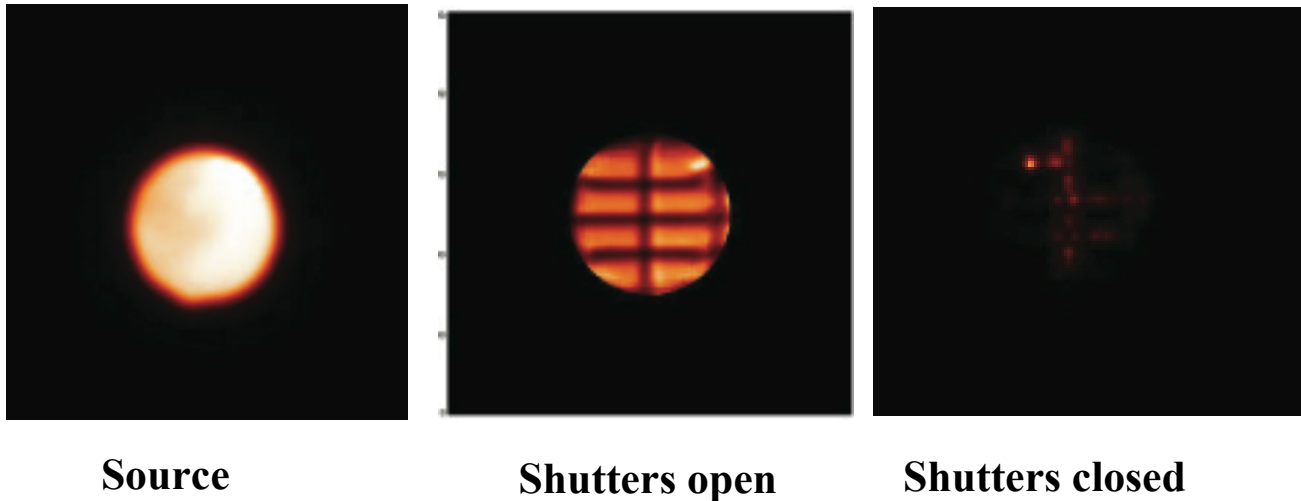


Figure 5. Shutter transmission and contrast are measured using a slightly extended $f/12$ source, to simulate the beam at the position of the microshutter array in NIRSpec. The ratio of the intensity of the unobstructed beam to that with the open shutters in place yields the open transmission. The ratio of the open shutter intensity to the closed shutter intensity is the contrast ratio. For this shutter, the ratio was $> 100,000$. The NIRSpec requirement is $> 2,000$ with a goal of 10,000.

4.2. Contrast

The contrast of the microshutter array is defined as the ratio of the transmission of a shutter when open to that measured when closed. This is an important parameter for the NIRSpec, because light leaking through closed shutters can cause excess photon noise in the spectra being measured, or systematic errors that will be difficult to remove from the spectra, especially in crowded fields. We have developed an optical bench that can provide a beam of similar focal ratio to that in the NIRSpec at the position of the microshutter array⁴. In the tests (Fig. 5), we have focused a slightly extended source on the shutter plane, and measured its total intensity with the shutter removed, with the shutter in place and open, and with the shutter in place and closed. From these measurements, we can determine the contrast ratio, and have found that for modest light shield overlap ($\sim 1 \mu\text{m}$), extremely high contrast ratios ($> 100,000$) can be achieved. A remaining challenge is to demonstrate that the high contrast ratio can be maintained over the operational life of the device.

4.3. Reliability

One of the most demanding requirements on the microshutter array is the reliability. At the beginning of life, there can be permanently open shutters in at most 1% of the rows, and less than 5% of the shutters can be permanently closed. At the end of life, less than 5% of the rows can have a permanently open shutter, while 20% of the array may be permanently closed. The much more stringent requirement on the open failures is due to the fact that the grating will disperse light from a permanently open shutter over much of an entire row of detectors along the dispersion direction, significantly reducing their utility. These operability requirements are stringent, and impose significant fabrication and testing requirements. Tests of arrays fabricated during the process development have been obtained which suggest that significant infant mortality of shutters may occur⁵. The probability of failure decreases proportionally with the number of cycles. Preliminary results from devices from a more mature version of the process show much less of this type of failure, so it is possible that we can produce arrays with little probability of failure in the required lifetime. If not, a burn in period followed by repairs will be required to reduce the probability of failure during the instrument life.

5. SUMMARY AND PLANS

We are developing microshutter arrays for use as the programmable field selection on the NIRSpec on JWST. Prototype arrays demonstrate actuatability and addressability, and reach the contrast goals of JWST. Two major tasks remain in this development, scaling the arrays up to the full 175 x 384 format and demonstrating the required reliability. Rapid progress is being made in both these areas, and the JWST schedule requires that these problems be resolved by Aug. 2005.

We are confident that microshutter arrays will meet the requirements of NIRSpec, and will provide an important enhancement of the capability of JWST.

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